Electrical Transformer Testing Handbook

Volume 4

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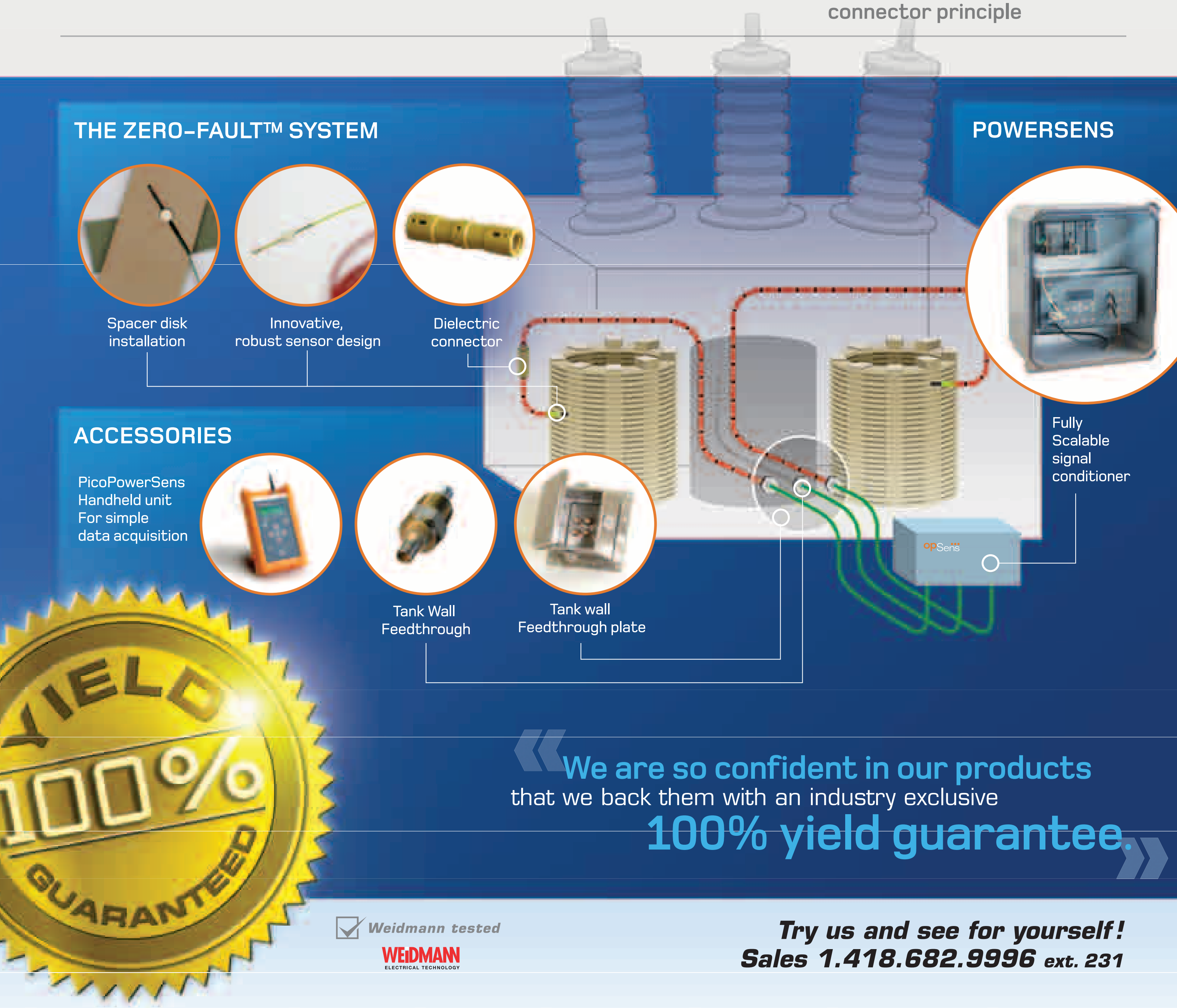
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TRANSFORMER BASICS

Tabtronics, Inc.

A transformer is an electrical device that transfers energy from one circuit to another purely by magnetic coupling. Relative motion of the parts of the transformer is not required for transfer of energy. Transformers are often used to convert between high and low voltages, to change impedance, and to provide electrical isolation between circuits.

INTRODUCTION

The transformer is one of the simplest of electrical devices. Its basic design, materials, and principles have changed little over the last one hundred years, yet transformer designs and materials continue to be improved. Transformers are essential in high voltage power transmission providing an economical means of transmitting power over large distances. The simplicity, reliability, and economy of conversion of voltages by transformers were the principal factors in the selection of alternating current power transmission in the "War of Currents" in the late 1880s. In electronic circuitry, new methods of circuit design have replaced some of the applications of transformers, but electronic technology has also developed new transformer designs and applications.

Transformers come in a range of sizes from a thumbnail-sized coupling transformer hidden inside a stage microphone to gigawatts units used to interconnect large portions of national power grids, all operating with the same basic principles and with many similarities in their parts.

Transformers alone cannot do the following:

Convert DC to AC or vice versa
Change the voltage or current of DC
Change the AC supply frequency.

However, transformers are components of the systems that perform all these functions.

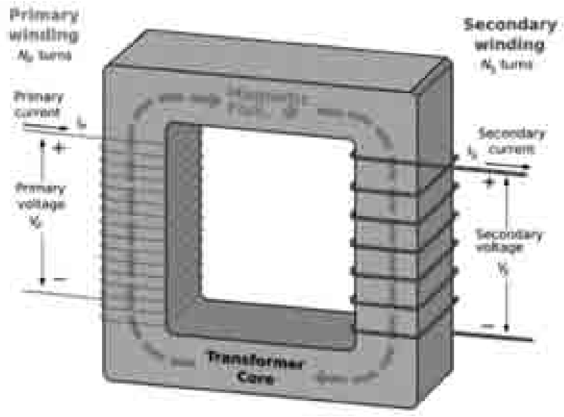
BASIC PRINCIPLES

AN ANALOGY

The transformer may be considered as a simple two-wheel 'gearbox' for electrical voltage and current. The primary winding is analogous to the input shaft and the secondary winding to the output shaft. In this comparison, current is equivalent to shaft speed, voltage to shaft torque. In a gearbox, mechanical power (speed multiplied by torque) is constant (neglecting losses) and is equivalent to electrical power (voltage multiplied by current) which is also constant.

The gear ratio is equivalent to the transformer step-up or step-down ratio. A step-up transformer acts analogously to a reduction gear (in which mechanical power is transferred from a small, rapidly rotating gear to a large, slowly rotating gear): it trades current (speed) for voltage (torque), by transferring power from a primary coil to a secondary coil having more turns. A step-down transformer acts analogously to a multiplier gear (in which mechanical power is transferred from a large gear to a small gear): it trades voltage (torque) for current (speed), by transferring power from a primary coil to a secondary coil having fewer turns.

FLUX COUPLING LAWS



An idealised step-down transformer showing resultant flux in the core

A simple transformer consists of two electrical conductors called the primary winding and the secondary winding. If a time-varying voltage is applied to the primary winding of turns, a current will flow in it producing a magnetomotive force (MMF). Just as an electromotive force (EMF) drives current around an electric circuit, so MMF drives magnetic flux through a magnetic circuit. The primary MMF produces a varying magnetic flux in the core (shaded grey), and induces a back electromotive force (EMF) in opposition to the MMF. In accordance with Faraday's Law, the voltage induced across the primary winding is proportional to the rate of change of flux:

$$v_P = N_P \frac{d\Phi_P}{dt}$$

Similarly, the voltage induced across the secondary winding is:

$$v_S = N_S \frac{d\Phi_S}{dt}$$

With perfect flux coupling, the flux in the secondary winding will be equal to that in the primary winding, and so we can equate Φ_P and Φ_S. Thus it follows that:

$$\frac{v_P}{v_S} = \frac{N_P}{N_S}.$$

Hence in an ideal transformer, the ratio of the primary and secondary voltages is equal to the ratio of the number of turns in their windings, or alternatively, the voltage per turn is the same for both windings. This leads to the most common use of the transformer: to convert electrical energy at one voltage to energy at a different voltage by means of windings with different numbers of turns.

The EMF in the secondary winding, if connected to an electrical circuit, will cause current to flow in the secondary circuit. The MMF produced by current in the secondary opposes the MMF of the primary and so tends to cancel the flux in the core. Since the reduced flux reduces the EMF induced in the primary winding, increased current flows in the primary circuit. The resulting increase in MMF due to the primary current offsets the effect of the opposing secondary MMF. In this way, the electrical energy fed into the primary winding is delivered to the secondary winding.

Neglecting losses, for a given level of power transferred through a transformer, current in the secondary circuit is inversely proportional to the ratio of secondary voltage to primary voltage.

For example, suppose a power of 50 watts is supplied to a resistive load from a transformer with a turn ratio of 25:2.

P = E·I (power = electromotive force · current)
50 W = 2 V · 25 A in the primary circuit

Now with transformer change:
50 W = 25 V · 2 A in the secondary circuit.

In a practical transformer, the higher-voltage winding will have more turns, of smaller conductor cross-section, than the lower-voltage windings.

Since a DC voltage source would not give a time-varying flux in the core, no back EMF would be generated and so current flow into the transformer would be unlimited. In practice, the series resistance of the winding limits the amount of current that can flow, until the transformer either reaches thermal equilibrium or is destroyed.

THE UNIVERSAL EMF EQUATION

If the flux in the core is sinusoidal, the relationship for either winding between its number of turns, voltage, magnetic flux density and core cross-sectional area is given by the universal emf equation:

$$E = 4.44 \cdot f \cdot N \cdot a \cdot B$$

Where in the sinusoidal root mean square voltage of the winding, f is the frequency in hertz, N is the number of turns of wire, a is the cross-sectional area of the core and B is the peak magnetic flux density in Tesla. The value 4.44 collects a number of constants required by the system of units.

INVENTION

Those credited with the invention of the transformer include:

- Michael Faraday, who invented an 'induction ring' on August 29, 1831. This was the first transformer, although Faraday used it only to demonstrate the principle of electromagnetic induction and did not foresee the use to which it would eventually be put.
- Lucien Gaulard and John Dixon Gibbs, who first exhibited a device called a 'secondary generator' in London in 1881 and then sold the idea to an American company Westinghouse. This may have been the first practical power transformer, but was not the first transformer of any kind. They also exhibited the invention in Turin in 1884, where it was adopted for an electric lighting system. Their early devices used an open iron core, which was later abandoned in favor of a more efficient circular core with a closed magnetic path.
- William Stanley, an engineer for Westinghouse who built the first practical device in 1885 after George Westinghouse, bought Gaulard and Gibbs' patents. The core was made from interlocking E-shaped iron plates. This design was first used commercially in 1886.
- Hungarian engineers Ottó Bláthy, Miksa Déri and Károly Zipernowsky at the Ganz company in Budapest in 1885, who created the efficient "ZBD" model based on the design by Gaulard and Gibbs.
- Nikola Tesla in 1891 invented the Tesla coil, which is a high-voltage, air-core, dual-tuned resonant transformer for generating very high voltages at high frequency.

PRACTICAL CONSIDERATIONS

CLASSIFICATIONS

Transformers are adapted to numerous engineering applications and may be classified in many ways:

- By power level (from fraction of a watt to many megawatts),
- By application (power supply, impedance matching, circuit isolation),
- By frequency range (power, audio, RF)
- By voltage class (a few volts to about 750 kilovolts)
- By cooling type (air cooled, oil filled, fan cooled, water cooled, etc.)
- By purpose (rectifier, arc furnace, amplifier output, etc.)
- By ratio of the number of turns in the coils

Step-up
The secondary has more turns than the primary.

Step-down
The secondary has fewer turns than the primary.

ISOLATING

Used to isolate the primary from the secondary side without change in the voltage level. The two coils have approximately equal numbers of turns although often there is a slight difference in the number of turns, in order to compensate for losses (otherwise the output voltage would be a little less than, rather than the same as, the input voltage).

VARIABLE TRANSFORMER

The primary and secondary have an adjustable number of turns which can be selected without reconnecting the transformer.

LOSSES

An ideal transformer would have no losses, and would therefore be 100% efficient. In practice, energy is dissipated due both to the resistance of the windings (known as copper loss), and to magnetic effects primarily attributable to the core (known as iron loss). Transformers are, in general, highly efficient, and large power transformers (around 100 MVA and larger) may attain an efficiency as high as 99.75%. Small transformers such as a plug-in "power brick" used to power small consumer electronics may be less than 85% efficient.

The losses arise from:

- Winding resistance
Current flowing through the windings causes resistive heating of the conductors.

- Eddy currents
Induced currents circulate in the core and cause its resistive heating.

- Stray losses
Not all the magnetic field produced by the primary is intercepted by the secondary. A portion of the leakage flux may induce eddy currents within nearby conductive objects such as the transformer's support structure, and be converted to heat. The familiar hum or buzzing noise heard near transformers is a result of stray fields causing components of the tank to vibrate, and is also from magnetostriction vibration of the core.

- Hysteresis losses
Each time the magnetic field is reversed, a small amount of energy is lost to hysteresis in the magnetic core. The level of hysteresis is affected by the core material.

- Mechanical losses
The alternating magnetic field causes fluctuating electromagnetic forces between the coils of wire, the core and any nearby metalwork, causing vibrations and noise which consume power.

- Magnetostriction
The flux in the core causes it to physically expand and contract slightly with the alternating magnetic field, an effect known as magnetostriction. This, in turn, causes losses due to frictional heating in susceptible ferromagnetic cores.

- Cooling system
Large power transformers may be equipped with cooling fans, oil pumps or water-cooled heat exchangers designed to remove the heat caused by copper and iron losses. The power used to operate the cooling system is typically considered part of the losses of the transformer.

HIGH FREQUENCY OPERATION

The universal transformer emf equation indicates that, at higher frequency, the core flux density will be lower for a given voltage. This implies that a core can have a smaller cross-sectional area and thus be physically more compact without reaching saturation. It is for this reason that the aircraft manufacturers and the military use 400 hertz supplies. They are less concerned with efficiency, which is lower at higher frequencies (mostly due to increased hysteresis losses), but are more concerned with saving weight. Similarly, flyback transformers which supply high voltage to cathode ray tubes operate at the frequency of the horizontal oscillator, many times higher than 50 or 60 hertz, which allows for a more compact component.

CONSTRUCTION

CORES, STEEL CORES

Laminated core transformer showing edge of laminations at top of unit. Transformers for use at power or audio frequencies have cores made of many thin laminations of silicon steel. By concentrating the magnetic flux, more of it is usefully linked by both primary and secondary windings. Since the steel core is conductive, it, too, has currents induced in it by the changing magnetic flux. Each layer is insulated from the adjacent layer to reduce the energy lost to eddy current heating of the core. A typical laminated core is made from E-shaped and I-shaped pieces, leading to the name "EI transformer".

Certain types of transformer may have gaps inserted in the magnetic path to prevent magnetic saturation. These gaps may be used to limit the current on a short-circuit, such as for neon sign transformers.

A steel core's magnetic hysteresis means that it retains a static magnetic field when power is removed. When power is then reapplied, the residual field will cause a high inrush current until the effect of the remnant magnetism is reduced, usually after a few cycles of the applied alternating current. Overcurrent protection devices such as fuses must be selected to allow this harmless inrush to pass. On transformers connected to long overhead power transmission lines, induced currents due to geomagnetic disturbances during solar storms can cause saturation of the core, and false operation of transformer protection devices.

Distribution transformers can achieve low off-load losses by using cores made with amorphous (non-crystalline) steel, so-called "metal glasses" - the high cost of the core material is offset by the lower losses incurred at light load, over the life of the transformer.

SOLID CORES

In circuits that operate above mains frequencies, up to a few tens of kilohertz, such as switch-mode power supplies, powdered iron cores are used. These materials combine a high magnetic permeability with a high bulk material resistivity. At even higher frequencies, typically radio frequencies, other types of core made of non-conductive magnetic materials, such as various ceramic materials called ferrites, are common. Some transformers in radio-frequency circuits have adjustable cores which allow tuning of the coupling circuit.

AIR CORES

High-frequency transformers may also use air cores. These eliminate the loss due to hysteresis in the core material. Such transformers maintain high coupling efficiency (low stray field loss) by overlapping the primary and secondary windings.

TOROIDAL CORES

Toroidal transformers are built around a ring-shaped core which is made from a long strip of silicon steel or perm-alloy wound into a coil, or from ferrite, depending on frequency. The strip construction ensures that all the grain boundaries are pointing in the optimum direction, making the transformer more efficient by reducing the core's reluctance. The ring shape eliminates the air gaps inherent in the construction of an EI core. The cross-section of the ring is usually square or rectangular, but more expensive cores with circular cross-sections are also available. The primary and secondary coils are wound concentrically to cover the entire surface of the core. This minimizes the length of wire needed, and also provides screening to prevent the core's magnetic field from generating electromagnetic interference.

Ferrite cores are used at frequencies up to a few tens of kilohertz to reduce losses, particularly in switch-mode power supplies.

Toroidal transformers are more efficient (around 95%) than the cheaper laminated EI types. Other advantages, compared to EI types, include smaller size (about half), lower weight (about half), less mechanical hum (making them superior in audio amplifiers), lower exterior magnetic field (about one tenth), and low off-load losses (making them more efficient in standby circuits), single-bolt mounting, and more choice of shapes. This last point means that, for a given power output, either a wide, flat toroid or a tall, narrow one with the same electrical properties can be chosen, depending on the space available. The main disadvantage is higher cost.

A drawback of toroidal transformer construction is the higher cost of windings. As a consequence, toroidal transformers are uncommon above ratings of a few kVA. Small distribution transformers may achieve some of the benefits of a toroidal core by splitting it and forcing it open, then inserting a bobbin contains primary and secondary windings.

When fitting a toroidal transformer, it is important to avoid making an unintentional short-circuit through the core. This can happen if the steel mounting bolt in the middle of the core is allowed to touch metalwork at both ends, which could result in a dangerously large current flowing in the bolt.

WINDINGS

In most practical transformers, the primary and secondary conductors are coils of conducting wire because each turn of the coil contributes to the magnetic field, creating a higher magnetic flux density than would a single conductor.

The winding material depends on the application. Small power and signal transformers are wound with insulated solid copper wire, often enameled. Larger power transformers may be wound with wire, copper or aluminum rectangular conductors, or strip conductors for very heavy currents. High frequency transformers operating in the tens to hundreds of kilohertz will have windings made of Litz wire, to minimize the skin effect losses in the conductors. Large power transformers use multiply-stranded conductors as well, since even at low power frequencies, non-uniform distribution of current would otherwise exist in large windings. Each strand is insulated from the others and the strands are arranged so that either at certain points in the winding or throughout the winding, each portion occupies different relative positions in the complete conductor. This "transposition" equalizes the current flowing in each strand of the conductor, and reduces eddy current losses in the winding itself. The stranded conductor is also more flexible than a solid conductor of similar size (see reference 1).

Windings on both primary and secondary of a power transformer may have external connections (called taps) to intermediate points on the winding to allow adjustment of the voltage ratio; taps may be connected to automatic on-load tap changer switchgear for voltage regulation of distribution circuits. Audio-frequency transformers used for distribution of audio to public address loudspeakers have taps to allow adjustment of power supplied to each speaker. A center-tapped transformer is often used in the output stage of an audio power amplifier in a push-pull circuit. Tapped transformers are also used as components of amplifiers, oscillators, and for feedback linearization of amplifier circuits.

INSULATION

The conductor material must have insulation to ensure the current travels around the core, and not through a turn-to-turn short circuit.

In power transformers, the voltage difference between parts of the primary and secondary windings can be quite large. Insulation is inserted between layers of windings to prevent arcing, and the transformer may also be immersed in transformer oil that provides further insulation. To ensure that the insulating capability of the transformer oil does not deteriorate, the transformer casing is completely sealed against moisture ingress. The oil serves as both cooling medium to remove heat from the core and coil and as part of the insulation system.

SHIELDING

Although an ideal transformer is purely magnetic in operation, the proximity of the primary and secondary windings can create a mutual capacitance between the windings. Where transformers are intended for high electrical isolation between primary and secondary circuits, an electrostatic shield can be placed between windings to minimize this effect.

Transformers may also be enclosed by magnetic shields, electrostatic shields, or both to prevent outside interference from affecting the operation of the transformer, or to prevent the transformer from affecting the operation of other devices (such as CRTs in proximity to the transformer).

COOLANT

All transformers must have some circulation of coolant to remove the waste heat produced by losses. Small transformers up to a few kilowatts in size usually are adequately cooled by air circulation. Larger "dry" type transformers may have cooling fans. Some dry transformers are enclosed in pressurized tanks and are cooled by nitrogen or sulfur hexafluoride gas.

The windings of high-power or high-voltage transformers are immersed in transformer oil - a highly-refined mineral oil that is stable at high temperatures. Large transformers to be used indoors must use a non-flammable liquid. Formerly, polychlorinated biphenyl (PCB) was used as it was not a fire hazard in indoor power transformers and it is highly stable. Due to the stability of PCB and its environmental accumulation, it is no longer permitted in new equipment. Today, nontoxic, stable silicone-based oils or fluorinated hydrocarbons may be used, where the expense of a fire-resistant liquid offsets additional building cost for a transformer vault. Other less-flammable fluids such as canola oil may be used but all fire resistant fluids have some drawbacks in performance, cost, or toxicity compared with mineral oil.

The oil cools the transformer, and provides part of the electrical insulation between internal live parts. It has to be stable at high temperatures so that a small short or arc will not cause a breakdown or fire. The oil-filled tank may have radiators through which the oil circulates by natural convection. Very large or high-power transformers (with capacities of millions of watts) may have cooling fans, oil pumps and even oil to water heat exchangers. Oil-filled transformers undergo prolonged drying processes, using vapor-phase heat transfer, electrical self-heating, the application of a vacuum, or combinations of these, to ensure that the transformer is completely free of water vapor before the cooling oil is introduced. This helps prevent electrical breakdown under load.

Oil-filled power transformers may be equipped with Buchholz relays - safety devices sensing gas buildup inside the transformer (a side effect of an electric arc inside the windings) and switching off the transformer.

Experimental power transformers in the 2 MVA range have been built with superconducting windings which eliminates the copper losses, but not the core steel loss. These are cooled by liquid nitrogen or helium.

TERMINALS

Very small transformers will have wire leads connected directly to the ends of the coils, and brought out to the base of the unit for circuit connections. Larger transformers may have heavy bolted terminals, bus bars or high-voltage insulated bushings made of polymers or porcelain. A large bushing can be a complex structure since it must both provide electrical insulation, and contain oil within the transformer tank.

ENCLOSURE

Small transformers often have no enclosure. Transformers may have a shield enclosure, as described above. Larger units may be enclosed to prevent contact with live parts, and to contain the cooling medium (oil or pressurized gas).

TRANSFORMER DESIGNS

AUTOTRANSFORMERS

An autotransformer has only a single winding, which is tapped at some point along the winding. AC or pulsed voltage is applied across a portion of the winding, and a higher (or lower) voltage is produced across another portion of the same winding. For voltage ratios not exceeding about 3:1, an autotransformer is less costly, lighter, smaller and more efficient than a two-winding transformer of a similar rating.

By exposing part of the winding coils and making the secondary connection through a sliding brush, an autotransformer with a near-continuously variable turns ratio can be obtained, allowing for very small increments of voltage.

POLYPHASE TRANSFORMERS

For three-phase power, three separate single-phase transformers can be used, or all three phases can be connected to a single polyphase transformer. The three primary windings are connected together and the three secondary windings are connected together. The most common connections are Y-_, _-Y, _-_ and Y-Y. A vector group indicates the configuration of the windings and the phase angle difference between them. If a winding is connected to earth (grounded), the earth connection point is usually the center point of a Y winding. There are many possible configurations that may involve more or fewer than six windings and various tap connections.

RESONANT TRANSFORMERS

A resonant transformer is one that operates at the resonant frequency of one or more of its coils. The resonant coil, usually the secondary, acts as an inductor, and is connected in series with a capacitor. If the primary coil is driven by a periodic source of alternating current, such as a square or sawtooth wave, each pulse of current helps to build up an oscillation in the secondary coil. Due to resonance, a very high voltage can develop across the secondary, until it is limited by some process such as electrical breakdown. These devices are therefore used to generate high alternating voltages. The current available from this type of coil can be much larger than that from electrostatic machines such as the Van de Graaff generator and Wimshurst machine. They also run at a higher operating temperature than standard units.

A voltage regulating transformer uses a resonant winding and allows part of the core to go into saturation on each cycle of the alternating current. This effect stabilizes the output of the regulating transformer, which can be used for equipment that is sensitive to variations of the supply voltage. Saturating transformers provide a simple rugged method to stabilize an ac power supply. However, due to the hysteresis losses accompanying this type of operation, efficiency is low.

INSTRUMENT TRANSFORMERS

CURRENT TRANSFORMERS

Current transformers used as part of metering equipment for three-phase 400 ampere electricity supply. A current transformer is designed to provide a current in its secondary which is accurately proportional to the current flowing in its primary. Current transformers are commonly used in electricity meters to facilitate the measurement of large currents which would be difficult to measure more directly.

Care must be taken that the secondary of a current transformer is not disconnected from its load while current is flowing in the primary as in this circumstance a very high voltage would be produced across the secondary.

Current transformers are often constructed with a single primary turn either as an insulated cable passing through a toroidal core, or else as a bar to which circuit conductors are connected.

VOLTAGE TRANSFORMERS

Voltage transformers (also known as potential transformers) are used in the electricity supply industry to measure accurately the voltage being supplied. They are designed to present negligible load to the voltage being measured.

PULSE TRANSFORMERS

A pulse transformer is a transformer that is optimized for transmitting rectangular electrical pulses (that is, pulses with fast rise and fall times and constant amplitude). Small versions called signal types are used in digital logic and telecommunications circuits, often for matching logic drivers to transmission lines. Medium-sized power versions are used in power-control circuits such as camera flash controllers. Larger power versions are used in the electrical power distribution industry to interface low-voltage control circuitry to the high-voltage gates of power semiconductors such as TRIACs, IGBTs, thyristors and MOSFETs. Special high voltage pulse transformers are also used to generate high power pulses for radar, particle accelerators, or other pulsed power applications.

To minimize distortion of the pulse shape, a pulse transformer needs to have low values of leakage inductance and distributed capacitance, and a high open-circuit inductance. In power-type pulse transformers, a low coupling capacitance (between the primary and secondary) is important to protect the circuitry on the primary side from high-powered transients created by the load. For the same reason, high insulation resistance and high breakdown voltage are required. A good transient response is necessary to maintain the rectangular pulse shape at the secondary, because a pulse with slow edges would create switching losses in the power semiconductors.

The product of the peak pulse voltage and the duration of the pulse (or more accurately, the voltage-time integral) are often used to characterize pulse transformers. Generally speaking, the larger this product, the larger and more expensive the transformer.

RF TRANSFORMERS

For radio frequency use, transformers are sometimes made from configurations of transmission line, sometimes bifilar or coaxial cable, wound around ferrite cores. This style of transformer gives an extremely wide bandwidth, however only a limited number of ratios (such as 1:9, 1:4 or 1:2) can be achieved with this technique. The ferrite increases the inductance dramatically while also lowering its Q factor. The cores of such transformers help performance at the lower frequency end of the band. This style of transformer is frequently used as an impedance matching to convert from 300 ohm balanced to 75 ohm unbalanced in FM receivers.

AUDIO TRANSFORMERS

Traditionally, in the valve amplifier, the function of the output transformer was to convert the low alternating current music signal (that had been imposed on top of the high-voltage direct current from the plate electrode of the final output tube) into a useable high-current/low-voltage level for conversion by the loudspeakers.

In early transistor amplifiers, such transformers were also used.

USES OF TRANSFORMERS

- Electric power transmission over long distances.
- High-voltage direct-current HVDC power transmission systems
- Large, specially constructed power transformers are used for electric arc furnaces used in steelmaking.
- Rotating transformers are designed so that one winding turns while the other remains stationary. A common use was the video head system as used in VHS and Beta video tape players. These can pass power or radio signals from a stationary mounting to a rotating mechanism, or radar antenna.
- Sliding transformers can pass power or signals from a stattionary mounting to a moving part such as a machine tool head. An example is the linear variable differential transformer,
- Some rotary transformers are precisely constructed in order to measure distances or angles. Usually they have a single primary and two or more secondaries, and electronic circuits measure the different amplitudes of the currents in the secondaries, such as in synchros and resolvers.
- Small transformers are often used to isolate and link different parts of radio receivers and audio amplifiers, converting high current low voltage circuits to low current high voltage, or vice versa.
- Balanced-to-unbalanced conversion. A special type of transformer called a balun is used in radio and audio circuits to convert between balanced circuits and unbalanced transmission lines such as antenna down leads. A balanced line is one in which the two conductors (signal and return) have the same impedance to ground: twisted pair and "balanced twin" are examples. Unbalanced lines include coaxial cables and strip-line traces on printed circuit boards. A similar use is for connecting the "single ended" input stages of an amplifier to the high-powered "push-pull" output stage.

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INSTRUMENT TRANSFORMERS TECHNICAL INFORMATION AND APPLICATION GUIDE

ABB

INTRODUCTION

Instrument transformers (ITs) are designed to transform voltage or current from the high values in the transmission and distribution systems to the low values that can be utilized by low-voltage metering devices. There are three primary applications for which ITs are used: metering (for energy billing and transaction purposes); protection control (for system protection and protective relaying purposes); and load survey (for economic management of industrial loads).

Depending on the requirements for those applications, the IT design and construction can be quite different. Generally, the metering ITs require high accuracy in the range of normal operating voltage and current. Protection ITs require linearity in a wide range of voltages and currents. During a disturbance such as system fault or over voltage transients, the output of the IT is used by a protective relay. The relay initiates an appropriate action (open or close a breaker, reconfigure the system, etc.) to mitigate the disturbance and to protect the rest of the power system.

Instrument transformers are the most common and economic way to detect a disturbance. Typical output levels of instrument transformers are 1-5 amperes and 115-120 volts for CTs and VTs, respectively.

There are several classes of accuracy for instrument transformers defined by the IEEE, CSA, IEC, and ANSI standards. Figure 1 presents a conceptual design of CTs and VTs.

Figure 2 shows how the polarity markers are used to keep the direction of current flow in the meters exactly the same, as if the primary circuit was carried through the meters. Grounding of the secondary circuit is most important, but in complicated three phase connections, the best point to ground is not always easily determined.

Figure 1: Current and Voltage Transformer Symbols and Simplified Concepts

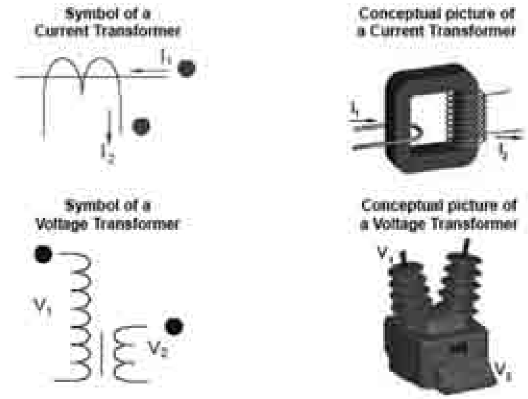
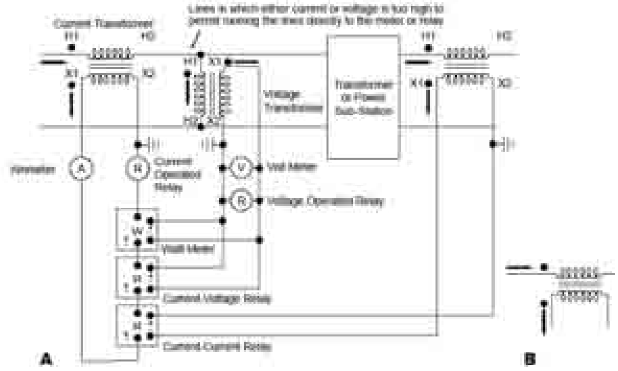

Symbol of a Current Transformer
I_1
I_2
Conceptual picture of a Current Transformer
I_1
I_2
Symbol of a Voltage Transformer
V_1
V_2
Conceptual picture of a Voltage Transformer
V_1
V_2

Figure 2: Instrument Transformer Connections



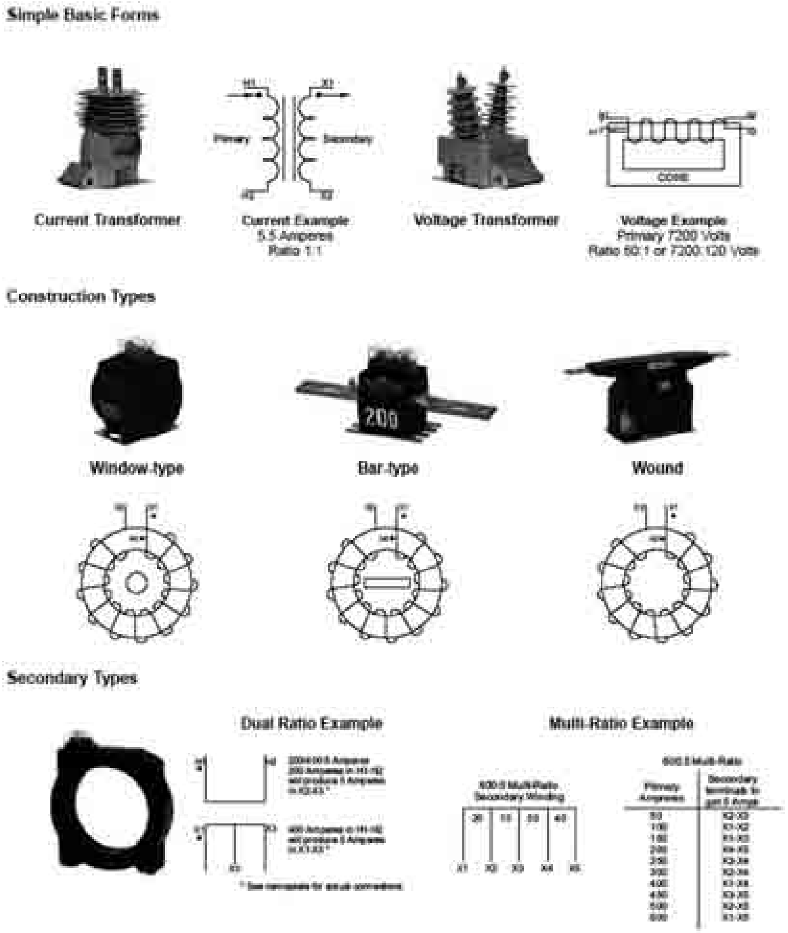
A. The current transformer is designed to connect in series with the line to transform the line current to the standard 5 amperes suitable for the meter or relay. The voltage transformer is designed to connect in parallel with the line to transform the line voltage to 115 or 120 volts suitable for the meter or relay. To keep the voltage at the meters and relays at a safe value, the secondary circuit must be grounded.

B. The polarity markers indicate the relative instantaneous directions of current in the windings. The polarity, or instantaneous direction of current, is of no significant difference for current-operated or voltage-operated devices. Correct operation of current-current, voltage-voltage, or current-voltage devices usually depends on the relative instantaneous directions.

TYPES OF CONSTRUCTION

The principal forms of construction used for instrument transformers, together with standard symbols according to IEEE Standard C57.13, are shown in Figure 3.

Figure 3: Types of Instrument Transformer Construction



MATERIALS USED IN CONSTRUCTION

In the 1970s, the insulating medium for the higher voltage (5-34.5 kV) units was butyl rubber. The material itself is excellent, but the pressures and temperatures necessary to use it as a dielectric were not conducive to the exacting clearances and geometries inside a voltage or current transformer. Without excess bracing, the core/coil assemblies would shift during molding and fail BIL testing. With enough bracing, the material flow inside the unit was restricted, increasing the possibility of voids. For these reasons, another dielectric insulating material was sought. Butyl rubber is still used by some manufacturers.

Cycloaliphatic epoxy (CEP) was first introduced in outdoor insulators in the late 1970s due to its very good resistance to humidity, ultraviolet (UV) radiation, outdoor pollutants, and chemicals. Its outstanding mechanical strength and dielectric properties were also highly desirable.

Aromatic polyurethane (PUR) elastomers are another cost effective insulation for medium-voltage electrical equipment. There are approximately fourteen general types of PUR that are successfully commercialized for a wide variety of applications, including instrument transformers. Thirteen of these types are called conventional rubber. That means they are mixed, milled, and molded by techniques which have been in use by the rubber industry since the 1920s.

Polyurethane rubber raw materials are liquid, which permits them to be pumped, metered, mixed, and dispensed by machines under very precise control of temperature and ingredient proportions. The liquid mixture enters the mold at vacuum pressure and is cured at slightly elevated temperatures. This unique characteristic allows molding of large parts which are completely uniform throughout. When compared to high pressure-molded butyl rubber and vacuum cast epoxies, PUR in general has the most forgiving process.

The fully cured PUR elastomers possess a desirable balance of ease of manufacturing (via vacuum casting), mechanical toughness (it is, after all, a rubber) and very good electrical properties.

In the early 2000s, a global epoxy resin supplier introduced a hydrophobic version of CEP called Hydrophobic Cycloaliphatic Epoxy (HCEP) to the market. HCEP is formulated to sustain surface hydrophobicity better than its CEP counterpart upon prolonged exposure to aggressive outdoor environments without sacrificing other desirable chemical and mechanical properties.

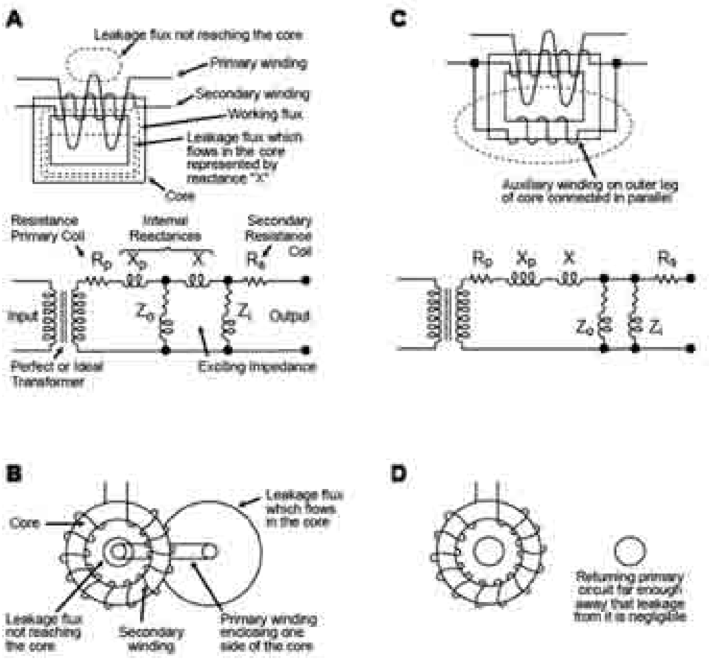
A hydrophobic insulation surface is desirable for outdoor applications because it prevents water from developing completely wetted, resistive conductive surfaces. Leakage currents are therefore reduced, which helps to reduce the flashover risk. The result is enhanced reliability. Furthermore, less discharge activity means less attack and therefore less surface erosion, which extends the transformer's life.

PERFORMANCE CHARACTERISTICS - EQUIVALENT CIRCUITS

The specific performance characteristics of instrument transformers are easily determined from the equivalent circuit. Figure 4 works well for most instrument transformers. For current transformers, the value of the reactance X is determined in a special way so that it represents the leakage flux. The flux flows in the part of the core represented by the left-hand exciting branch of the equivalent circuit shown in Figure 4.

An additional winding (or windings) placed over the outer leg(s) of the core and connected back in parallel with the secondary winding, as shown in Figure 4, can keep the leakage flux out of the core. The leakage reactance is then effectively connected ahead of both exciting branches as shown in Figure 4. This difference is important for current transformers because leakage flux in the core affects current ratio. It also improves the performance of current transformers and subjects their performance to simple calculation. Voltage transformers are designed so the through impedance (RS, R, XP, and X) is as low as possible, while current transformers are designed so the excitation impedance (Zo and Z) is as high as possible. Neither transformer is very good at performing the function of the other.

Figure 4: Equivalent Circuits


A
Leakage flux not reaching the core
Primary winding
Secondary winding
Working flux
Leakage flux which flows in the core represented by reactance "X"
Core
Resistance Primary Coil
Internal Reactances
Secondary Resistance Coil
R_p
X_p
X
R_s
Input
Z_o
Z_i
Output
Perfect or Ideal Transformer
Exciting Impedance
C
Auxiliary winding on outer leg of core connected in parallel
R_p
X_p
X
R_s
Z_o
Z_i
B
Core
Leakage flux which flows in the core
Leakage flux not reaching the core
Secondary winding
Primary winding enclosing one side of the core
D
Returning primary circuit far enough away that leakage from it is negligible

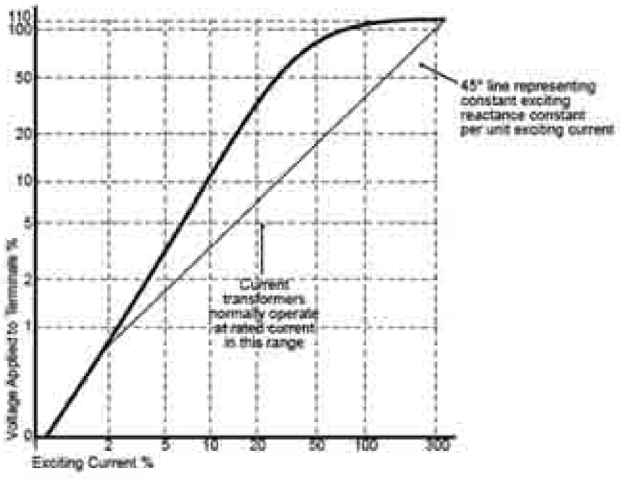
A. A typical transformer and its equivalent circuit. The leakage flux is shown entering the outer part of the core and is represented by reactance X. The reactance develops voltage applied to the exciting branch Zo, which represents the outer side of the core. The series impedance, RP + RS + j (XP + X), is responsible for the loss of voltage in transformation. The voltage transformers are carefully designed to keep this impedance as low as possible. The loss of current in transformation is due to current by-passed by the exciting branches, Zo and Zi. Current transformers are specially designed to keep these by-pass exciting impedances as high as possible.

B. A common construction of HV or EHV current transformer. Leakage flux enters the core even though the winding is uniformly wound over a ring core. The equivalent circuit is the same as for Figure A.

C. A construction used in HV or EHV current transformers. The parallel auxiliary winding effectively keeps the leakage flux out of the core so that the leakage reactance in the equivalent circuit is effectively ahead of the exciting branches. This simplifies the calculation of the current by-passed through Zo and Zi.

D. A typical bushing current transformer. This resembles the transformer in B but has only negligible leakage flux in the core because the return conductor is far away. This transformer still has a good deal of leakage reactance, but the leakage flux does not enter the core in significant amount. The reactance is ahead of the by-pass branches Zo and Zi so that the performance as a current transformer can be easily calculated.

Figure 5: Typical Transformer Saturation Curve



The value of through impedance is constant, but the value of excitation impedance is variable. The exciting impedances representing the exciting currents for the two parts of the core depend on the voltage applied to them, the current flowing in them, or flux density in the core. The easiest way to understand Zo and Zi, which are of primary importance in current transformers, is to draw "saturation" curves showing how the current flowing into the exciting branch varies with the voltage applied, as shown in Figure 5. The curve is usually plotted for the combination of Zo and Zi in parallel.

Voltage transformers are designed such that the operating point on the saturation curve, as shown in Figure 5, is typically at a relatively high voltage. This is subject to the limitation that this point must not be so high that the exciting current itself is excessive. Voltage transformers are designed to work without excessive exciting current up to 110% of rated voltage. The IEEE standard for performance requires good performance also at 90% voltage. Figure 5 shows that the exciting current will not reach a higher per unit value, with consequent increase of voltage loss from exciting current, at voltages over the range of 5% to 110%.

THE EFFECT OF RATIO ERROR AND PHASE ANGLE ON WATTMETER READINGS

Ideal transformers induce the same voltage per turn in the secondary winding as that applied to the primary voltage transformers. They also produce the same ampere-turns in the secondary as circulated in the primary current transformers, to deliver any desired ratio of primary to secondary voltage or current. In the actual transformer shown in Figure 4, the secondary current output is deficient by the amount of current bypassed by the exciting branches, Zo and Z, and the secondary output voltage is deficient by the voltage drop in the transformer through impedance. Note: 1. the ratio of turns is usually adjusted to "compensate" for the losses in the transformer. Because of this "compensation", the actual secondary output can be higher than would be expected from the marked ratio.

The transformer nameplates show a “marked ratio”, usually an even number, such as 20 to 1. The actual ratio of primary to secondary quantity may be slightly higher or lower than the marked value by an amount1 called ratio error, which is defined in IEEE C57.13 as ratio correction factor (RCF). For instance, if the actual ratio is 20.2 to 1, then the RCF is 1.01 and the ratio error is 1%. The secondary output may be slightly out of phase with the primary input. This error is called phase angle (usually measured in minutes) and is designated as positive if the secondary output leads the primary input.

If the ratio correction factor exceeds 1.0, the meters will read low and the readings should be multiplied by the correction factor. The effect of phase angle, however, is not as obvious. The transformer correction factor (TCF) determines reasonable limits for RCF and phase angle. This depends on both RCF and phase angle and may be used to correct the reading of a wattmeter. TCF is based on the fact that if the power factor of a metered power load is 60% lagging (represents the usual minimum power factor of actual power loads being metered by watt hour meters), 2.6 minutes of phase angle in the current (or voltage) transformer output will cause 0.1% error in the wattmeter reading. **Voltage Transformers** The RCF and phase angle must be determined at the specific burden involved. However, as with an actual measurement, these values apply to the secondary voltage at the transformer terminals. If the leads from the transformer to the burden are very long, they may have sufficient impedance to introduce additional voltage drop and error. The voltage drop in the leads can be calculated from the current drawn from the transformer and the impedance of the leads. If it is of appreciable magnitude in percent of secondary voltage, the addition to ratio and phase angle error may be calculated according to the vector diagram in Figure 6 and the formulas:

Percent Ratio will be increased by:

$$\frac{I_S\,(R_L \cos\ \theta + X_L \sin\ \theta)}{E_S} \times 100$$

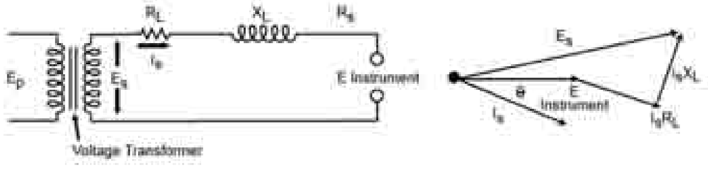
Add this amount to the percent ratio of the transformer to get the actual percent ratio of primary to burden voltage.

The Phase Angle will be increased by

$$\frac{I_S\,(R_L \sin\ \theta\ - X_L \cos\ \theta)}{E_S} \times 3438 \text{ Minutes}$$

Add this amount to the phase angle of the transformer (algebraically) to get the actual phase difference between primary and burden voltages.

Figure 6: Effect of Leads in Voltage Transformers

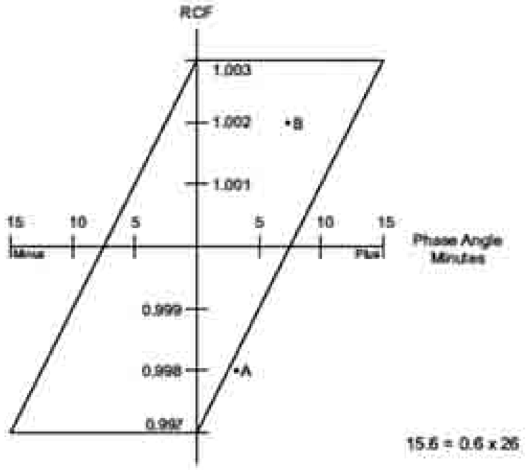


L and XL represent the resistance and reactance in the leads. Method for calculating impedance drops in the leads and resulting ratio and phase angle errors.

Current Transformers The ratio correction factor and phase angle must be determined at the specific burden and current involved. Current transformer characteristics at special burdens can only be determined by an actual measurement. The test burden must duplicate the actual burden, including the secondary leads. The secondary terminal voltage and power factor must be identical to that of the installation. In addition, these measurements need to be made and applied at the actual service currents.

Accuracy Classifications for Metering Figures 7 and 8 provide an explanation of accuracy classes for current and voltage transformers. These figures show the Accuracy Classes as adopted by IEEE, as well as the special limitations which apply to current and voltage transformers. IEEE C57.13 has recognized 0.3% as a reasonable error limit and has designated this as “Accuracy Class 0.3.”

Figure 7: The Basic 0.3 Class Parallelogram for Current Transformers



The Figure 7 parallelogram outlines the area in which the measurements of RCF and Phase Angle at 100% current must plot to designate the transformer accuracy as 0.3 Class with TCF within the limits of 0.997 and 1.003. For example, if the RCF at a given burden at 100% current is 0.998 (99.8% Ratio) and the Phase Angle is 3.5 minutes, point A is seen to fall outside the parallelogram.

Another example: RCF = 1.002, Phase Angle 5 minutes, representing greater absolute error, point “B” is now inside the parallelogram and meets the required limits for 0.3 Accuracy Class. In the second case, TCF is less than 1.003 because the effect of phase angle on the wattmeter compensates for the error in ratio.

IEEE C57.13 recognizes that current transformers naturally have greater errors at lower currents, and that error at low current does not usually represent significant error in total registration of kilowatt hours. This permits twice the error at 10% that is permitted at 100% current. The error at the maximum current permitted by the Thermal Rating Factor of the transformer (a multiplier of 1.5 or 4.0 applied to many transformers) is limited to the same value at 100% current.

Other Accuracy Classes: In addition to the 0.3 Class, C57.13 recognizes the 0.6 and 1.2 Classes in which the permissible errors are twice as great (0.6%) and twice again (1.2%) as compared to the 0.3 Class. Any one of these classes may be selected for specification by the user depending on whether 0.3%, 0.6%, or 1.2% seems reasonable for a given application.

The Figure 8 parallelogram outlines an area in which the measurements of RCF and Phase Angle at 100% (also at 110%) voltage must plot to designate the transformer accuracy as 0.3 Class with TCF within the limits of 0.997 and 1.003. For example, if the measured RCF at a given burden is 0.999 and the phase angle is -8 minutes, point A is seen to fall outside the parallelogram.

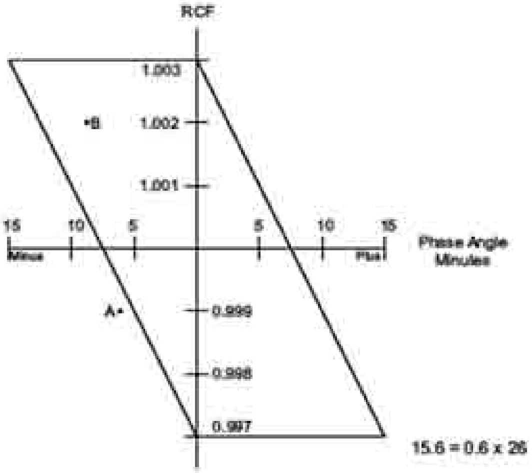
Another example: RCF = 1.002, Phase angle is -10 minutes, both representing greater absolute errors, but the point "B" is now inside the parallelogram and meets the required limits for the 0.3 Class. In the second case, the TCF is less than 1.003 because the effect of phase angle on the wattmeter compensates for the phase angle.

The reason for the reversed appearance of Figure 8 compared to Figure 7 is that phase angle in the current transformer brings the secondary current more nearly in phase with the load voltage, increasing the wattmeter reading. In the voltage transformer, the effect is just the opposite.

C57.13 requires that the limits also be met at 90% voltage; in reality, the performance at voltages down to 5% is not significantly different at the same burden connected to the transformer secondary. The error limits required by C57.13 apply not only at a given burden, but also at zero burden.

Other Accuracy Classes: In addition to the 0.3 Class, C57.13 recognizes the 0.6 and 1.2 Classes in which the permissible errors are twice as great (0.6%) and twice again (1.2%) as compared to the 0.3 Class. Any one of these classes may be selected for specification by the user depending on whether 0.3% , 0.6%, or 1.2% seems reasonable for a given application.

Figure 8: The Basic 0.3 Class Parallelogram for Voltage Transformers



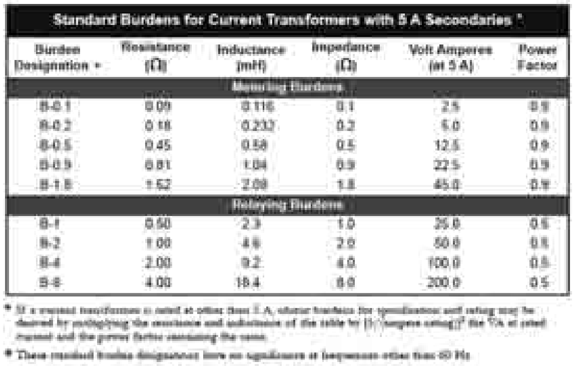
BURDENS

The errors in ratio and phase angle depend on the impedance connected to the secondary of the transformer. This impedance is commonly referred to as "burden". The calculations required for determining the performance of a transformer when different burdens are applied are beyond the scope of this discussion. Therefore, the standard burdens as outlined in IEEE C57.13 are used to represent typical service conditions. Each transformer is rated according to its performance at these standard burdens.

STANDARD BURDENS FOR CURRENT TRANSFORMERS

Many current transformers supply only a limited number of watt-hour meter elements with a limited number of runs. For metering and relaying applications, IEEE C57.13 has established the standard burdens as given in Figure 9.

Figure 9: Standard Burdens for Current Transformers



Standard Burdens for Current Transformers with 5 A Secondaries *

Burden Designation +	Resistance (Ω)	Inductance (mH)	Impedance (Ω)	Volt Amperes (at 5 A)	Power Factor
Metering Burdens					
B-0.1	0.09	0.116	0.1	2.5	0.9
B-0.2	0.18	0.232	0.2	5.0	0.9
B-0.5	0.45	0.58	0.5	12.5	0.9
B-0.9	0.81	1.04	0.9	22.5	0.9
B-1.8	1.62	2.08	1.8	45.0	0.9
Relaying Burdens					
B-1	0.50	2.3	1.0	25.0	0.5
B-2	1.00	4.6	2.0	50.0	0.5
B-4	2.00	9.2	4.0	100.0	0.5
B-8	4.00	18.4	8.0	200.0	0.5

ACTUAL BURDENS FOR CURRENT TRANSFORMERS

Actual devices connected to instrument transformers often include an inductor with an iron core, which usually means that the inductance is not constant but varies during the cycle, and varies differently with different currents. Exact analysis of current transformer performance with such devices is difficult. Fortunately, the impedances of most instruments and meters are sufficiently constant that no appreciable error is introduced by considering them to be constant. Many electromechanical relays, however, have variable impedance. Analysis of the transformer performance is usually based on an equivalent value at normal current. This can be justified on the basis that the burden at higher current is usually less and thus the current transformer will perform better than expected from the equivalent burden.

STANDARD BURDENS FOR VOLTAGE TRANSFORMERS

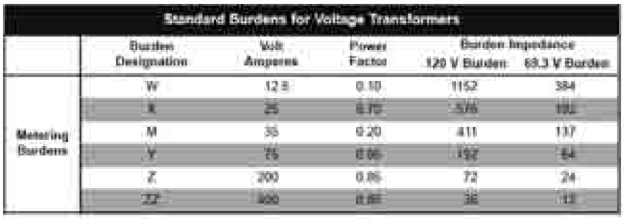
Some relays operate from two or more sources of current: differential (current-current), or power or impedance-measuring (current-voltage) relays. If the two circuits are magnetically coupled by the relay, the burden on one source is affected by the current in the other source, and vice versa. Most of the two-source relays act by balance-beam or other mechanical coupling, so that the burdens are fixed.

The standard burdens to be used for testing and comparing voltage transformers are rated at 120 volts and at 69.3 volts. IEEE C57.13 specifies that the 120 volt-rated burden will be used for any transformer with the secondary voltage in the range of 115 to 120 volts, while the 69.3 volt burden will be used for any transformer with the secondary voltage in the range of 65 to 72 volts. This means that the actual volt amperes in the burden in a given test may be different than the nominal value of the burden in volt amperes. For instance, if the standard burden is

25 volt amperes, the actual burden when it is used for testing a transformer with 115 volt secondary is (115/120)2 or .918 times the nominal value of 25.

The burdens rated 69.3 volts have impedance only one-third of that of burdens rated 120 volts and they should not be used in testing or rating transformers rated at 115 to 120 volts. Transformers rated at 115 or 120 volts should be treated as 115 or 120 volt transformers, and if they are actually used at reduced voltage, the performance will not be different if the 120 volt burden is used as a basis for performance. This is because the performance of a transformer down to voltages of about 5% of its rating is not significantly different from the performance at 100% voltage. Refer to Figure 10 for standard burdens for voltage transformers as outlined in IEEE C57.13

Figure 10: Standard Burdens for Voltage Transformers



Standard Burdens for Voltage Transformers					
	Burden Designation	Volt Amperes	Power Factor	Burden Impedance	
				120 V Burden	69.3 V Burden
Metering Burdens	W	12.5	0.10	1152	384
	X	25	0.70	576	192
	M	35	0.20	411	137
	Y	75	0.85	192	64
	Z	200	0.85	72	24
	ZZ	400	0.85	36	12

CURRENT TRANSFORMERS: ACCURACY CLASSES FOR RELAYING

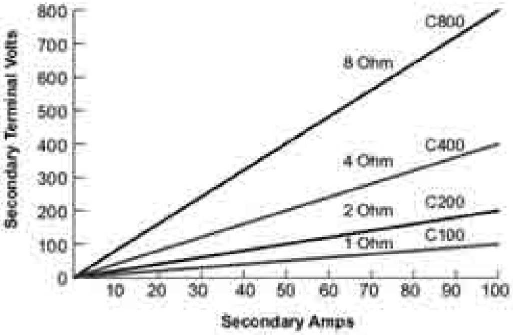
Relaying accuracy classes for CTs are defined with a “C” or a “T” classification. “C” indicates that the transformer ratio can be calculated. These are transformers which are constructed so that the effect of leakage fluxes on its performance is negligible. “T” indicates the transformer where the leakage flux has an appreciable effect on the ratio. Since the calculation of the excitation current by-passed is a tedious process, the performance of the transformer can only be determined by test.

The basis for classification of performance for relaying is an error limit of 10% at any current from 1.0 to 20 times normal. The accuracy class is the description of how much voltage the transformer can supply to the output circuit (burden), without the CT core going into saturation.

For example, a transformer that can supply a 2 ohm output circuit (burden) at 100 A [20 times normal current (5 A)] or 200 V, without saturating the core and within a 10% error limit, is classified as 200 accuracy class. Refer to Figure 11.

Standard accuracy classes, which may be assigned for a relaying current transformer, are 50, 100, 200, and 800. If a C200 transformer can supply 100 A secondary outputs at exactly 10% error into a 2 ohm burden, then the exciting branch is not over 10 amperes. If the current is lower, then the burden can be higher without exceeding the output voltage limit if a transformer can carry 2 ohms at 50 amperes and deliver 200 volts. However, if the burden is 1 ohm at 200 amperes, it will not work since the internal impedance will be significant in relation to the 1 ohm burden.

Figure 11: Accuracy Standard Chart for Class C Current Transformers



PARTIAL DISCHARGES IN TRANSFORMER INSULATION

Partial discharges (PD) are minute electrical discharges that result from the electric field stresses imposed on any insulation system. As the name suggests, they do not cause a complete electrical breakdown of the insulation, so their short term effect is not catastrophic.

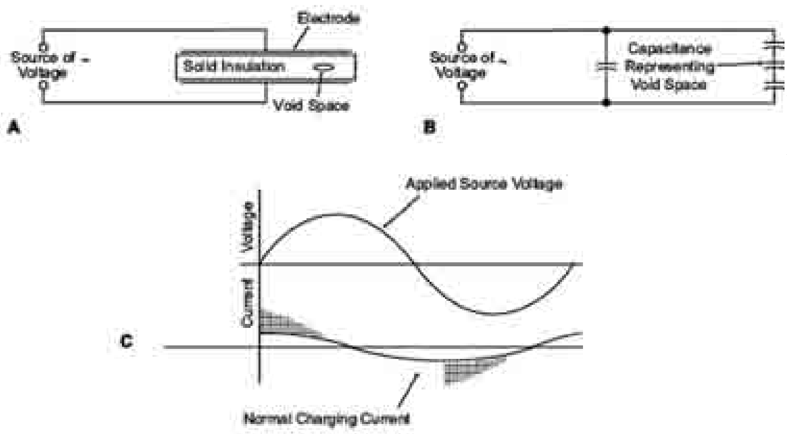
Over the long term, if the electric field stresses are high, PD can slowly deteriorate the quality of the insulation. In solid insulation systems (such as in instrument transformers), PD can occur where a void or discontinuity in solid insulation is introduced (Figure 12). Because of the difference between dielectric properties of a void (filled with air or gas) and solid material, the localized electrical stress in the void can be higher than in a solid. This will cause a void to break down although the voltage across the solid will remain (Figure 12). These localized void breakdowns, resulting in small, high frequency current impulses, can be detected by using sensitive instrumentation. Sophisticated, specialized analysis of PD patterns can then be used to gain insight to the nature of PD, its possible location, and mitigation.

PD is measured in the pico Coulombs (pC) unit of electrical charge. After many years of deliberation, different standards for different electrical equipment (ANSI, IEC, IEEE) do not consistently agree on the allowable or maximum limits of PD.

Manufacturers of ITs use different ways of minimizing or controlling the level of PD:

- Control manufacturing processes (casting, curing, temperatures, vacuum, viscosities, etc.) to minimize the introduction of voids
- Develop shielding materials and techniques to minimize electric field stress enhancement
- Fill voids with dielectric gas to lower the risk of void breakdown
- Use insulation materials with similar dielectric constants for the solid insulation system

Figure 12: Partial Discharges



A. A sample of solid insulation between electrodes, which forms a capacitor, can have a void as shown.

B. The electrically equivalent capacitance network.

C. Applied voltage and the corresponding PD current caused by breaking down the void.

OVERLOADING, OVERHEATING AND AGING

All insulation materials are deteriorated by the combination of overheating and exposure to moisture, oxygen in air, and UV radiation in outdoor conditions. ABB insulation systems are designed to withstand degradation caused by all of these environmental factors.

IEEE Standard C57.13 recognizes two classes of insulation in so far as resistance to temperature is concerned: (a) 55°C temperature rise and (b) 80°C rise, both over a 30°C daily average ambient temperature. These values are the average temperature rise of the winding (as measured by rise of resistance) during the temperature test at rated maximum continuous current. The

Guides for Loading recognize that these temperatures can be considerably exceeded for short periods of time without causing excessive deterioration of the insulation (reference Section 10 of IEEE C57.13).

MAINTENANCE AND INSPECTION TESTING OF INSULATION

Instrument transformer users routinely test new transformers, as well as transformers in service, to ensure their adequacy for service. It is rarely possible for the end user to run complete series of tests, but there are some things the user can do for reassurance. Measurement of the resistance of each winding to ground (when one winding is measured, ground all other winding terminals) with a megger will indicate if something has happened to reduce the resistance values. Such an incident is most improbable on encapsulated transformers. All ABB insulated current and voltage transformers should have typical readings from the high voltage winding to the low voltage winding, and ground above 1 Megohm per volt at 25°C.

Insulation resistance should be measured at ambient temperature (not over 30°C) because it decreases rapidly at higher temperatures.

VOLTAGE RATINGS

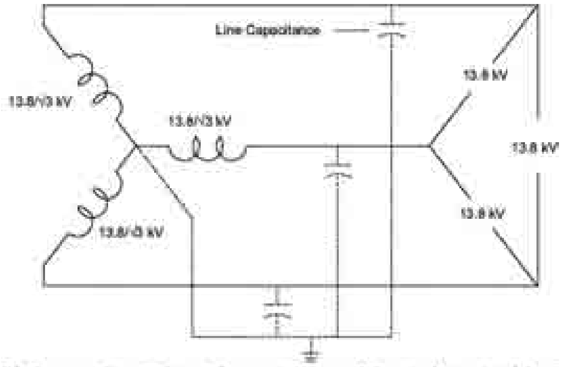
Current transformers are always rated at the line-to-line voltage of the three-phase system on which they will operate. A 13.8 kV current transformer, for example, is designed for use on a 13.8 kV three-phase system. The actual voltage from the current transformer primary winding to ground is only 13.8/e3 or 7.9 kV as shown in Figure 13.

VOLTAGE RATINGS FOR CURRENT TRANSFORMERS

In the Transformer Standards IEEE C57.13, an insulation class, which has the appearance of a system voltage rating, is associated with each of the standard arrays of dielectric tests (60 Hertz and impulse voltage). It has become standard practice to apply transformers on systems with actual voltage higher than the insulation class value. This is done on the basis that if the power system is designed such (grounded, usually) that the line-to-ground voltage can never be more than 70% or 80% of the line-to-line value, lower-voltage-rated lightning arresters can be used and the insulation is protected from all the higher voltages to which it might otherwise be subjected.

The transformer test voltages consist of a full wave impulse, chopped waves, 60 Hertz applied, and induced voltage test according to the schedule outlines in IEEE C57.13

Figure 13: Equivalent System Diagram



Whether or not this neutral is actually connected to ground, the natural symmetry of the ci coil and the equal line capacitors to ground will cause the neutral to assume ground potenti

VOLTAGE RATINGS FOR VOLTAGE TRANSFORMERS

The voltage which may be applied to a voltage transformer is limited not only by the permissible voltage to ground (as it is in a current transformer) but by the insulation between turns, between layers, and coil sections. It is also limited by the ability of the core to carry enough magnetic flux to induce the voltage.

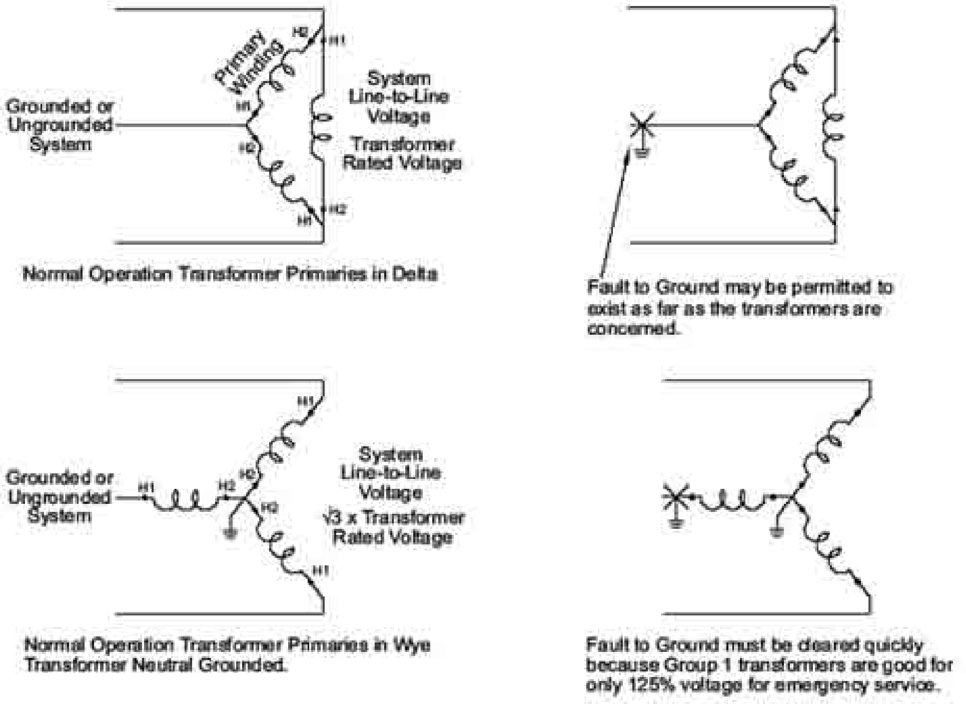
The voltage transformer is somewhat different from the distribution transformer, and certainly from the power transformer, in having a very limited capacity to store energy.

OVER VOLTAGE LIMITS

IEEE C57.13 recognizes five groups of voltage transformers for different capabilities and connections. These groups are explained by Figures 14 through 18. All transformers, according to IEEE C57.13, are capable of operating continuously, and of maintaining their accuracy at 110% of rated voltage.

As indicated in the figures, Group 2 transformers need do no more than this, and Group 1 transformers must be able to operate (but not necessarily maintain accuracy) at 125% voltage during emergencies, while Group 3 and 4 transformers must be able to operate for one minute at line-to-line voltage, which is e3 times their rating. Group 5 must be able to operate (but not necessarily maintain accuracy) at 140% voltage for one minute.

Figure 14: Application Limitation - Group 1 Voltage Transformers


Primary Winding
H2
H1
H1
H2
H1
H2
Grounded or Ungrounded System
System Line-to-Line Voltage
Transformer Rated Voltage
Grounded or Ungrounded System
H1
H2
H2
H2
H1
H1
System Line-to-Line Voltage
√3 x Transformer Rated Voltage

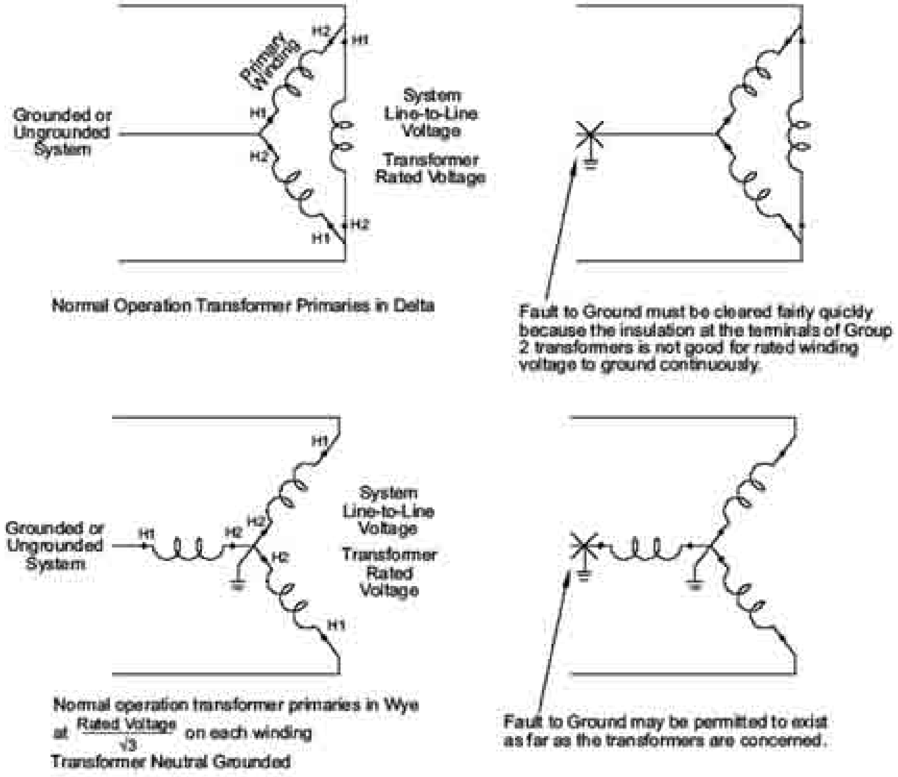
Normal Operation Transformer Primaries in Delta

Fault to Ground may be permitted to exist as far as the transformers are concerned.

Normal Operation Transformer Primaries in Wye Transformer Neutral Grounded.

Fault to Ground must be cleared quickly because Group 1 transformers are good for only 125% voltage for emergency service.

Figure 15: Application Limitation - Group 2 Voltage Transformers


Primary Winding
H2
H1
H1
H2
H1
H2
Grounded or Ungrounded System
System Line-to-Line Voltage
Transformer Rated Voltage
Grounded or Ungrounded System
H1
H2
H2
H2
H1
H1
System Line-to-Line Voltage
Transformer Rated Voltage

Normal Operation Transformer Primaries in Delta

Fault to Ground must be cleared fairly quickly because the insulation at the terminals of Group 2 transformers is not good for rated winding voltage to ground continuously.

Normal operation transformer primaries in Wye at $\frac{\text{Rated Voltage}}{\sqrt{3}}$ on each winding Transformer Neutral Grounded

Fault to Ground may be permitted to exist as far as the transformers are concerned.

Figure 17: Application Limitation - Group 4 Voltage Transformers

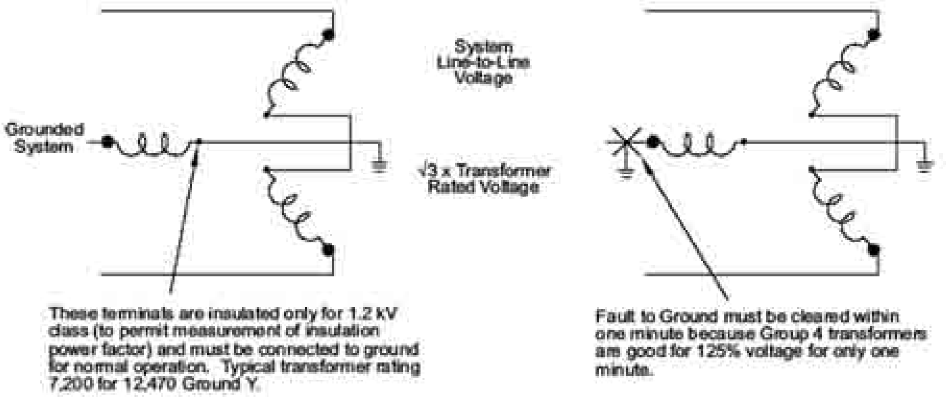
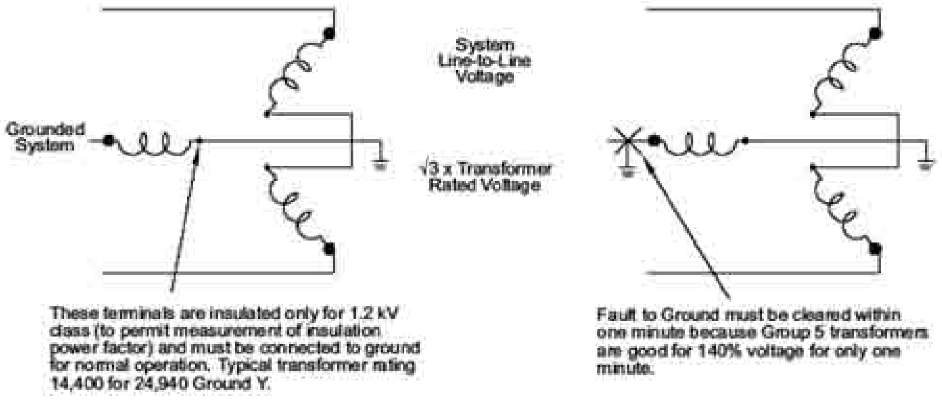

System Line-to-Line Voltage
Grounded System
√3 x Transformer Rated Voltage
These terminals are insulated only for 1.2 kV class (to permit measurement of insulation power factor) and must be connected to ground for normal operation. Typical transformer rating 7,200 for 12,470 Ground Y.
Fault to Ground must be cleared within one minute because Group 4 transformers are good for 125% voltage for only one minute.

Figure 18: Application Limitation - Group 5 Voltage Transformers


System Line-to-Line Voltage
Grounded System
√3 x Transformer Rated Voltage
These terminals are insulated only for 1.2 kV class (to permit measurement of insulation power factor) and must be connected to ground for normal operation. Typical transformer rating 14,400 for 24,940 Ground Y.
Fault to Ground must be cleared within one minute because Group 5 transformers are good for 140% voltage for only one minute.

POWER QUALITY

Power quality is an important consideration in designing any power system. Distribution systems are especially vulnerable to power quality problems. These problems should be taken into account when selecting and purchasing equipment. Distances for power delivery, density of loads, and customer concentrations are among the aspects that differ between the US ANSI market and the European IEC market. Power quality problems include:

- Voltage sags and dips
- Momentary interruptions (flicker)
- Harmonics (harmonic current and/or harmonic voltages)

VOLTAGE SAGS AND DIPS

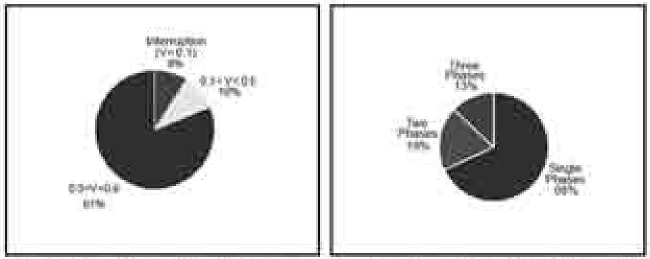
Voltage sags and dips are associated with switching or fault events in the power system that cause voltages on adjacent or neighboring circuits to partially collapse. These events can last from a few milliseconds to more than a second.

MOMENTARY INTERRUPTIONS

Momentary interruptions are the same type of power system events as voltage sags and dips, but are caused by lightning and other transients. The primary difference is that momentary interruptions occur primarily in the circuits directly involved in the event rather than in an adjacent circuit. Momentary interruptions are more severe power quality problems than voltage sags and dips.

Figures 19A & 19B show statistics of voltage sags and momentary interruptions in a typical ANSI power system.

Figures 19A and 19B: Distribution of RMS Events



19A. Pie-chart showing the statistics of voltage sags and interruptions. Note most events (81%) are sags (between 0.5 pu and 0.9 pu).

19B. Pie-chart showing the statistics of all power quality event types. Note most events (68%) are single phase.

HARMONICS

Harmonics are caused by non-linear loads. The nature of nonlinear power equipment causes a perfectly sinusoidal voltage waveform to result in currents containing other frequencies. A sinusoidal current can cause the generation of non-sinusoidal voltages. Non-linear power equipment includes saturated transformers, motors, and generators, but is primarily associated with power electronics. The act of triggering or switching a Silicon Controlled Rectifier (SCR), a diode, an Insulated Gate Bipolar Transistor (IGBT), or a Gate Turn-Off device (GTO) is, in principle, a non-linear operation. Power electronics devices such as Adjustable Speed Drives (ASDs), or Variable Speed Drives (VSDs) can exhibit a high level of harmonics, often more than 100% Total Harmonic Distortion (THD). In the case of ASDs, this level of harmonics varies with the selected rpm of the motor and mechanical load on the shaft.

Harmonics are unwanted events in distribution systems. They can cause excessive heating and damage to neutral connections and cables, and can saturate instrument transformers. Harmonics may also precipitate from the original location of the non-linear equipment to other locations like feeders and loads. They also may cause false tripping or malfunctioning of equipment, false readings from the CTs and VTs especially sensitive relays, computer loads, other ASDs, and Programmable Logic Controllers (PLCs). There are a variety of techniques to mitigate and control the level of harmonics, and industry standards regulating harmonics (see IEEE 519, Standard Practices and Requirements for Harmonic Control in Electrical Power Systems, or IEC 555/1000-3).

Possible mitigation procedures include reconfiguring the system, re-sizing the cables or transformers to include additional loading due to harmonic currents, or installing filters and harmonic blockers. It is important to remember that these measures work for some, but not for all harmonics. Often a comprehensive study has to be performed to determine the level of harmonic currents, their impact on the power system, and possible suppression measures.

In real systems, one disturbance in the system can cause a cascade of other disturbances. For example, a lightning surge (fast over voltage transient) traveling along an overhead feeder line can cause a flashover and subsequent short circuit in a substation supplying an industrial plant which, in turn, can cause abnormal acceleration of a local generator and so on.

SERVICE CONDITIONS

A voltage transformer is connected across the line or line ground, and is loaded to a greater or lesser degree depending on the number of devices connected in parallel at the secondary terminals (Figure 20). As the load is increased, the curves for ratio error and phase angle will show how the accuracy is affected.

OVERLOAD AND SHORT CIRCUIT CAPABILITY

If accuracy is not important, the load can be increased to the thermal volt-ampere rating, the maximum which can be carried without overheating. Voltage transformers must be able to withstand an accidental short circuit for one second.

A current transformer's primary is connected in series with the line and must carry whatever current flows in the line. The burden impedance connected to the secondary terminals affects the accuracy, as shown by the curves for ratio error and phase angle, but generally has no significant effect on temperature.

Because watt-hour meters are usually capable of carrying at least 400% of rated current continuously, many of those current transformers used almost exclusively with watthour meters have been designed specifically to carry two to four times normal current.

Also, because many of those current transformers are used almost exclusively in enclosed switchgear, they must be designed to operate in a high ambient temperature (55°C), they will carry 1.33 times normal current in a normal (30°C daily average) ambient temperature. The factor designating the continuous current capacity in terms of rated current at 30°C ambient is called thermal current rating factor. Standard values are 1.33, 1.5, 2.0, 3.0 and 4.0. The continuous thermal rating factor is based on 30°C average ambient temperature unless otherwise noted.

The IEEE Guides for Loading recognize that transformer insulation can withstand a considerable degree of overheating for a short time without severe deterioration. For example, in the event of a line short circuit, the fault current may easily be fifty times the rated current of the current transformer, but will probably flow for not over one second. IEEE C57.13 permits a 250°C temperature for this very short time (compared to 95°C average continuous winding temperature). All current transformers are assigned a one-second thermal current limit which denotes how much current they will carry (usually denoted in terms of times normal rated current) for one second. For durations up to five seconds, current transformers will carry currents lower than this.

The transformer will carry more current for a time less than one second according to the same rule, up to the mechanical current limit (which is also given for standard current transformers.) At this limit of current, the electro-mechanical forces tending to separate the primary and secondary oils, become high enough to damage the transformer.

The mechanical current limit is specified in terms of times normal rated current, as is the thermal one-second limit, but it is always assumed that the current may be fully offset initially. If it is known that the current cannot be initially fully offset, the current transformer will be able to withstand mechanically a larger RMS value of current, larger than its rated mechanical limit.

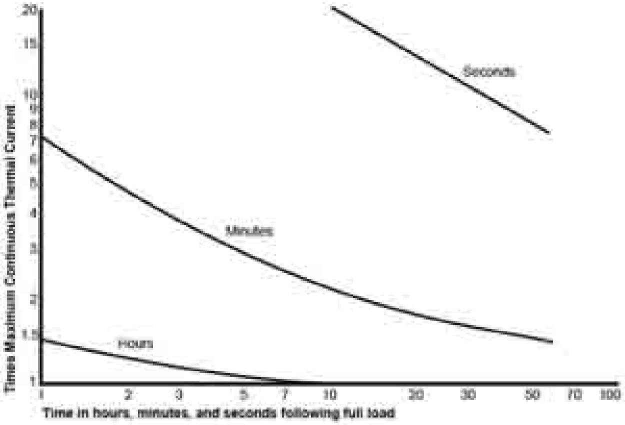
The temperature at these high currents and short times (less than five seconds) cannot be measured, but is always calculated on the basis that all heat generated by the current is stored in the copper for the duration (not over five seconds) of the high current.

Currents higher than the rated value, but less than the five second limit, can be determined by the rules set forth in the IEEE Guides for Loading. The calculation for any given transformer is lengthy, and as a general guide for standard transformers, the curves of Figure 20 can be used.

HIGHER AND LOWER AMBIENT TEMPERATURES

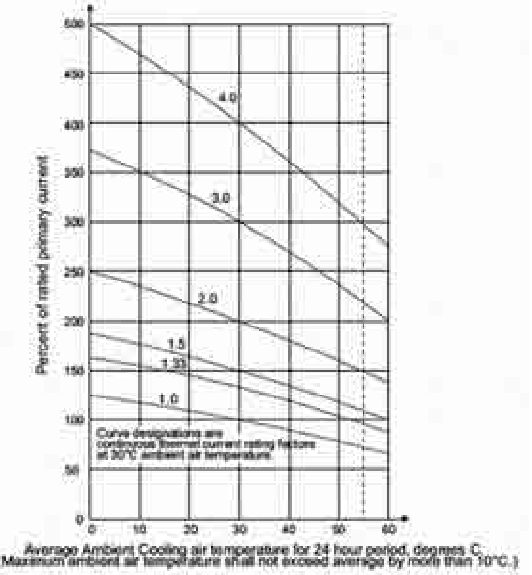
At temperatures over the standard 30°C, daily average ambient temperature current transformers should be derated 1% for each degree over (up to 55°C ambient). At temperatures under 30°C, they may be updated 0.75% for each degree (down to 0°C). Special application CTs are available where bus bar temperature is as high as 135°C (refer to Figure 21).

Figure 20: Overload Capability of Current Transformers



Recommended guide for short time loading of current transformers following rated load for 0.1% loss of life. Transformers so loaded will reach temperatures in excess of 55°C rise over ambient. Loading according to this curve is not safe if the ambient exceeds 30°C on the average, or if the overload occurs more often than once a day

Figure 21: 55°C Rise Current Transformer Thermal Loading Guide



OPEN-CIRCUIT VOLTAGE IN CURRENT TRANSFORMERS

Figure 2 (page 11) shows that the line current must flow through the current transformer, and Figure 4 (page 13) shows that if the secondary circuit is accidentally opened, all the current will have to pass through the exciting current branches of the equivalent circuit. This will develop a high voltage across the exciting branch, which will appear as a high voltage at the secondary terminals.

Because this voltage is limited by saturation of the core, the RMS value measured by a voltmeter may not appear to be dangerous. As the current cyclically passes through zero, the rate of change of flux at current zero is not limited by saturation, and is very high indeed. This induces extremely high peaks or pulses of voltage.

These high peaks of voltage may not register on the conventional voltmeter, but they can break down insulation and are dangerous to personnel. Current transformers are insulated to withstand, for emergency operation, secondary peak voltages up to 3500 volts.

This takes care of the smaller transformers with relay accuracy class under T200, but if open-circuit of larger transformers is probable, some protective circuit should be permanently connected to the secondary terminals. In general, open-circuit of the secondary terminals should be considered as a serious accident.

The actual open-circuit voltage peak is difficult to measure accurately because it exists only as very short peaks. The method outlined in the Test Methods Section of IEEE C57.13 represents an excellent compromise between precision and feasibility.

PERMANENT MAGNETIZATION OF CURRENT TRANSFORMER CORES

If a system short-circuit occurs, with a current of several times normal, the voltage at the burden may be rather high. The flux density in the equivalent exciting reactance (the core of the current transformer) may be high enough that if the fault current is abruptly interrupted, the core may be permanently magnetized at a fairly high flux density. This is often referred to as residual magnetization.

If the secondary circuit of the current transformer is accidentally opened, the flux density will become very high and even if the circuit is immediately closed again, the core may be left with permanent magnetization.

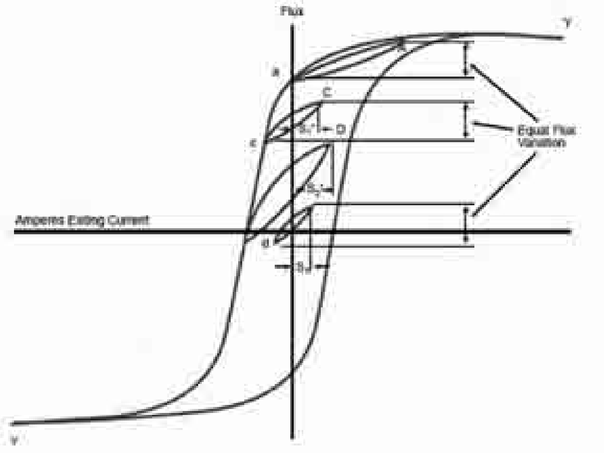
When normal current and flux variation is restored, the flux variation starts from the residual value and varies as shown in Figure 22. If the flux starts to increase from point a, the flux variation cannot be maintained in loop a-A in Figure 22, because such a loop would require direct current to maintain it in its offset position. The flux loop must shift down to the symmetrical (around the vertical axis) loop c-C. As it shifts down it actually generates a small direct current in the secondary circuit. The secondary burden will establish the rate of change. The flux variation will stay in this loop indefinitely.

The slope of the loop c-C will be less than the slope of the normal, completely symmetrical loop at the origin The peak exciting current S1´ will be higher than the normal exciting current S1. If the alternating flux density increases, the hysteresis loop moves to d-D and the slope of this loop becomes nearly equal to the symmetrical loop. The exciting current S2´ is still greater than the symmetrical value, but not as much greater in percent, as the difference between S1´ and S1.

The final result is that the effective exciting current, which causes ratio error and phase angle, is increased if the core becomes permanently magnetized. This will usually cause no more than 0.1% and 3 minutes of additional error in practical metering transformers at metering burdens10. The difference is less dependent on burden and current than might be expected. This is because the increase in exciting current from permanent magnetism is less at low flux variation, and moves to a constant ampere-turn value as the flux variation increases.

If precision measurement of ratio and phase angle is important, especially if ratio and phase angle measurements made at different times or in different laboratories are to be compared, demagnetization of the core by the conventional method of applying an alternating voltage high enough to circulate rated current in the secondary winding, reducing it gradually to zero, is desirable. (See IEEE C57.13). 10. at 100% current.

Figure 22: Permanent Magnetism in Current Transformers



To allow loop a-A to exist, a direct current must flow, requiring a DC voltage. This in turn requires a downward change in flux to induce it, with the result that the loop shifts down to c-C which is symmetrical about the vertical axis and requires no direct current. Operation is stable over this loop. The iron is permanently magnetized by having been at point a, and the loop c-C will not of itself shift down further. Imposition of a still higher AC flux variation will cause the larger loop d-D, shifted down from c-C. A very high flux density will restore the original symmetrical loop y-Y.

VOLTAGE TRANSFORMER CONNECTED LINE-TO-GROUND ON AN OTHERWISE UNGROUNDED SYSTEM

An ungrounded system is always actually grounded, although perhaps very poorly, by the capacitance and resistance of its insulation-to-ground, as shown in Figure 24. If a voltage transformer is connected from one line-to-ground it is, in effect, connected in parallel with a capacitor. The equivalent circuit is shown in Figure 24. Figure 24 also shows how parallel resonance can occur between transformer and capacitor, and how it can cause a very high voltage with destruction of the voltage transformer. If examination of a voltage transformer which has failed shows only the primary winding uniformly roasted from end-to-end, gross over-excitation is undoubtedly the cause and “ferroresonance” can be suspected. It is called ferro-resonance because this resonance depends on partial saturation of an iron core.

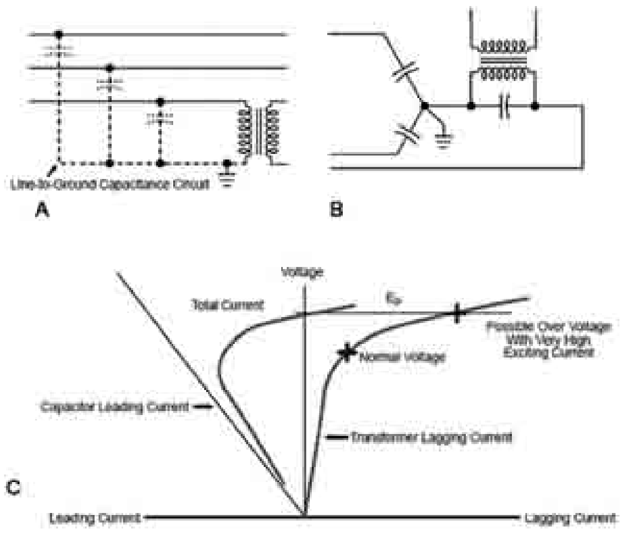
The number of combinations of constants which can cause ferroresonance is large, and the analysis of the circuit and prediction of possible destructive voltage is not simple. For ABB transformers of present and foreseeable future manufacture, this works out as shown in Figure 23.

These high loadings may cause errors greater than 0.3%, but transformers connected line-to-ground on an ungrounded system are rarely used for metering in the ANSI market (units connected line-to-line are more common). If three transformers are connected in Y on the primaries, the secondaries should never be connected in Delta.

Figure 23: Watt Loading - Ferro-resonance Prevention

Voltage Class (Primary)	Watt Loading on Secondary to Prevent Ferro-resonance	Approximate Ohms Equivalent Resistance per Phase (120 V)	Connected Across Corner of Broken Delta
To 500	200	72	216
7200-15000	500	29	87
25000 and up	750	20	60

Figure 24: Ferro-resonance Voltage Transformers


Line-to-Ground Capacitance Circuit
A
B
Voltage
Total Current
E_0
Possible Over Voltage With Very High Exciting Current
Normal voltage
Capacitor Leading Current
Transformer Lagging Current
C
Leading Current
Lagging Current

A. Line-to-ground capacitance circuit

B. Equivalent Y circuit

C. Approximate possible curve of current (neglecting resistance components) showing that at some particular value of voltage (E_0) the capacitor and transformer's reactive current total zero, representing infinite impedance, with the result that the voltage-to-ground on this line may reach E_0. This is a high enough value that excessive exciting current will burn out the primary winding.

AUXILIARY CURRENT TRANSFORMERS

Many circuit problems can be solved by connecting one current transformer to supply another current transformer, usually called an Auxiliary current transformer, shown in Figure 25.

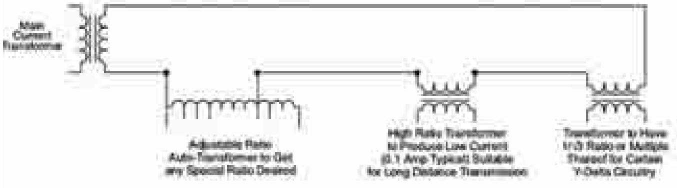
Auxiliary current transformers perform like other current transformers, but there are certain problems associated with their use which merit discussion.

First, the auxiliary current transformer constitutes an additional burden on the main current transformer, which usually increases the errors of the main current transformer.

Second, the performance of auxiliary current transformers is not usually as good as the performance of main current transformers. This is because the auxiliary current transformer is designed to impose as small a burden as possible on the main current transformer. This means its own burden capacity must be relatively low.

These two considerations mean that the errors of transformation, when an auxiliary current transformer is used, will typically be three times the value which might be expected with a single transformer. However, the special functions which can be performed by the auxiliary current transformer, as indicated in Figure 25, often dictate their use.

Figure 25: Auxiliary Current Transformers


Main Current Transformer
Adjustable Ratio Auto-Transformer to Get any Special Ratio Desired
High Ratio Transformer to Produce Low Current (0.1 Amp Typical) Suitable for Long Distance Transmission
Transformer to Have 1/√3 Ratio or Multiple Thereof for Certain Y-Delta Circuitry

FUSING VOLTAGE TRANSFORMERS

Primary fuses are primarily used with voltage transformers to take the transformer off the line in the event of an internal failure.

This prevents a failed VT from becoming an L-G fault, which requires the breaker to interrupt the customer's electric service. Since modern transformers are much more reliable than older ones, the fuses may never operate due to internal transformer failure. Transformer failure may still be caused by overload or short circuit on the secondary, however. If such failure occurs, it may involve other apparatuses, perhaps causing an outage.

Modern fuses are more substantial and reliable than older fuses, so the chance of fuse failure is minimized. Only the exceptional installation will be so dependent on continuity of voltage that the transformer must be connected solidly to the primary circuit. With modern fuses, the principal disadvantages are the cost of fuses and mounting and the space they require.

Most primary fuses will also protect the transformer against partial short circuit in the primary winding and against secondary short circuit. Some operators choose fuses which will not operate on secondary short circuit conditions.

All voltage transformer fuses will interrupt only a certain maximum fault current, therefore current limiting fuses are utilized. These current limiting fuses have higher interrupting ratings and can, in most cases, be used without external resistors to limit the current.

Primary fuses may be mounted on indoor transformers at the factory or they may be in separate mountings. Generally, separate mountings increase the cost and the space required for installation.

Whether to use fuses or not is determined by the operator's established practice, but operation without fuses has proven satisfactory in the majority of installations. The same considerations apply for outdoor transformers, but separately mounted fuses in their own mountings must be used. They are not mounted on the transformer.

The use of secondary fuses is relatively rare and is a matter of personal choice with the operator. Such fuses should be rated so that they will carry the secondary current indicated by the thermal VA rating of the transformer, but should fault in a short time at any higher current to protect the transformer. If mechanical failure of a fuse occurs and is not quickly detected, a considerable loss of revenue or protection may occur.

NEW DESIGN TECHNOLOGIES

Cost-effective, highly reliable electrical equipment is the result of a design process that combines optimized electrical and mechanical design features, efficient use of the best insulation material available, and highly refined manufacturing processes. This innovative approach is used on the next generation of ABB instrument transformers.

ADVANCED DESIGN TECHNOLOGIES

Wider availability of advanced simulation software has provided engineers with many tools to develop new products and associated tooling without incurring large prototyping expenses.

In the next generation design of instrument transformers, ABB uses Ansoft's Maxwell® 3D electrostatic simulation software. This program calculates electric field stress distribution on the surface and inside the cast electrical device. For each insulation material candidate, different field stress distribution is obtained, depending on the dielectric properties of the material. Furthermore, the engineers can vary the conditions of the environment outside the simulation model to obtain field stress distribution specific to the environment.

The 3D-based design features are then imported into an ABB-proprietary software package (Reactive Molding RAMZES). This program optimizes the casting process and parameters, and calculates the resulting mechanical stresses and strains that develop inside the casting. Optimum mechanical robustness can be designed into the product through the variations of these casting parameters.

NEW MATERIAL TECHNOLOGIES

To yield the most reliable and affordable transformers, hydrophobic cycloaliphatic epoxy (HCEP) was configured into the electrostatic simulation model for product optimization. HCEP was developed by a global epoxy supplier using a proprietary formulation and special processing techniques to produce an improved outdoor epoxy. It sustains surface hydrophobicity better than its cycloaliphatic (CEP) counterpart upon prolonged exposure to aggressive outdoor environments, without sacrificing other desirable chemical and mechanical properties. (The advantageous characteristics of hydrophobic insulation surfaces have been previously discussed in the Technology Review section.) The resulting outdoor equipment possesses the following attributes:

- Improved weatherability and outdoor aging
- Better performance in heavily polluted environments
- Enhanced reliability and life expectancy of the product

NEW PROCESS TECHNOLOGIES

In the early stages, a vacuum-encapsulating process was most commonly used for epoxies. This more forgiving process eliminated the costly mechanical reinforcement of the core-coil assembly as required with the high pressure molding of butyl rubber.

During the 1980s, liquid injection casting of epoxies was introduced. The process was further automated and called automatic pressure gelation (APG). The APG process effectively shortens the encapsulating cycle time and has become the process of choice for epoxies.

The best design utilizing the best material still does not guarantee a reliable and long-lasting performance if it is not properly manufactured.

Although the APG process has been applied to epoxy casting for many years, the large window of casting parameters such as temperature, pressure, and curing time still presents a great challenge on how to optimize the process to obtain a superior product.

A trial and error approach is one way, but this leads to high prototyping costs and considerable evaluation time. As previously mentioned, the use of advanced simulation software (RAMZES) greatly shortens this exercise and allows engineers to efficiently optimize the casting process. When the APG process is coupled with the latest resin handling, mixing, and process control technologies, the result is a reliable, robust, and cost-effective product.

NEW SENSING TECHNOLOGIES

Parallel to the instrument transformers, the new techniques of measuring voltage and current are becoming commercially available.

VOLTAGE SENSING

Resistive voltage dividers are becoming a commercially viable alternative to measuring voltage. Although they draw slightly larger (resistive) current, they can be embedded in a cast of solid dielectric material (such as epoxy or polyurethane) and provide a stable output in a wide frequency range, including high order harmonics. The voltage from the resistive divider is equal to:

$$V_{SEC} = V_{PRI} * \frac{R_{SEC}}{R_{PRI} + R_{SEC}}$$

Capacitive voltage dividers have been in high-voltage testing for a long time. They provide a stable output proportional to the ratio of capacitances.

$$V_{SEC} = V_{PRI} * \frac{C_{PRI}}{C_{PRI} + C_{SEC}}$$

Capacitive voltage dividers have very high inherent impedance so they have to be connected to a high-impedance (light) burden. With the advancement of electronic relays and meters, this is becoming a commercially viable option for some applications.

Optical voltage sensors are available for high voltage applications where the insulation line-to-ground is a major concern. Optical voltage sensors are based on the electro-optical phenomenon called Kerr effect by which a light-wave is polarized depending on the electric field generated by the voltage in the system. The technology is available to be used in distribution systems as well, but some improvements in cost and complexity of the optical systems are still needed.

CURRENT SENSING

Rogowski coils or linear couplers are essentially air-core transformers that use a power conductor as a primary winding, and an air-core coil wrapped around it as a secondary. The difference is that the primary current induces a secondary voltage signal in the Rogowski coil (not a current), which is a proportional derivative of the primary current dI/dt. This requires some careful processing of the dI/dt signal to convert to the true measurement of the primary current. Again, with the advancement of the electronic signal processing, these devices are now commercially available. Rogowski coils are very linear and do not saturate, even under extreme current conditions and high frequencies.

Magneto-optical phenomenon, called Faraday's effect, can be used to measure the current as well. When polarized light passes around the conductor with the current, the magnetic field associated with the current changes the polarization angle of the light.

The change can be measured optically and converted to the electrical signal, proportional to the primary current. Optical transducers are inherently good for very high voltages since they do not require any electrical connection to the primary phase conductors.

The devices are linear over their entire current range.

THE FUNDAMENTALS OF CURRENT SENSE TRANSFORMER DESIGN

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TT electronics / MMG

ABSTRACT

The following paper will first review the basic principles of operation of a Current Sense Transformer and then follow a simplified design procedure. The design procedure will take into account the effects of temperature and frequency and how they relate to the choice of a magnetic core.

INTRODUCTION

Current sense transformers (CTs) are used in a variety of applications ranging from power management to precise current measurement in the automotive telecommunications, computer, industrial, consumer and medical industries. A current sense transformer is essentially a standard transformer whose primary is placed in series with a conductor carrying AC current.

The secondary is usually terminated in a resistance and the voltage on the secondary is more or less proportional to the current in the primary. Some CTs are designed to produce a voltage output which accurately tracks the AC component of the current in the primary; a linear design.

Others may be designed to merely produce a change in output for a significant change in input current so that a logic device or fault circuit may be triggered. This type would not be linear.

BASIC PRINCIPLES OF OPERATION

The equivalent circuit of a typical current transformer is shown in figure 1.

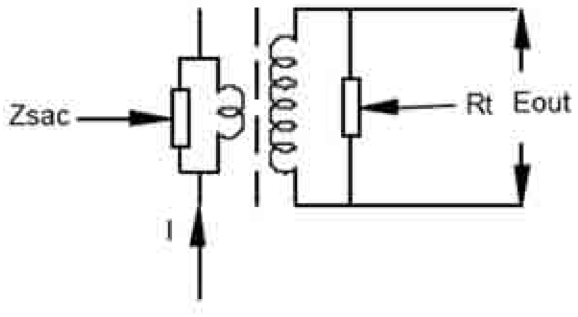


Figure 1

This standard design uses an accurate and specific resistive termination on the secondary. By transformer action, the loading effect of this resistance is transferred to the primary and appears as a shunt resistance across the primary. The parallel combination of this shunt resistance and the impedance of the primary winding form the impedance through which the current flows.

Typically, the transformer is designed so that the impedance of the primary winding is much greater than the shunt resistance reflected into the primary side and thus the primary impedance is mostly resistive. This shunt resistance acts as a current viewing resistor for AC current and it is this AC voltage drop that gets transferred to the secondary. It is this AC shunt resistance that the circuit sees and it is relatively easy to keep its value very low so as to have minimal effect on the circuit.

Because of the isolation feature of the current sense transformer, it can be placed at any desired location in a circuit, including above ground, to monitor current there.

DESIGN PROCEDURE

Typical starting points, or inputs, to the design process are the following:

- Primary turns (*Np*)
- Sensitivity (*S*)
- Desired series AC impedance (*Zsac*)
- Maximum current rating (*Imax*)
- Minimum frequency response (*fmin*)
- Desired design results or outputs would include:
- Secondary turns (*Ns*)
- Secondary termination resistance (*Rt*)
- Minimum inductance factor (*ALmin*)

The suggested design steps using the inputs listed above are as follows:

1. The desired series AC impedance (*Zsac*) introduced into the circuit by the current transformer can be expressed in volts per ampere instead of ohms. Using this figure as the volts per ampere in the primary side of the transformer and using the desired sensitivity (*S*) in volts per ampere at the secondary, the turns ratio (*n*) is calculated.

$$n = \frac{S}{Z_{sac}}$$

2. Calculate secondary turns (*Ns*) using the primary turns (*Np*) and the turns ratio.

$$N_s = n \cdot N_p$$

3. Calculate the secondary termination resistance (*Rt*) using the turns ratio and the series AC impedance at the primary.

$$R_t = Z_{sac} \cdot n^2$$

4. The minimum primary inductance required (*Lp*) is a function of how accurate and linear the volts per ampere versus current transfer function of the transformer needs to be. A good rule of thumb for an accurate and linear transformer is to design for minimum primary inductance whose inductive reactance is 100 times the primary Zsac at the minimum low frequency (*fmin*) design point.

$$L_p \min = X_L (2\pi \cdot f_{\min})$$

5. Calculate the required inductance factor to obtain the required primary inductance (*Lp*) with the specified number of primary turns (*Np*).

$$A_L = \frac{L_p \min}{N_p^2}$$

DESIGN EXAMPLE

Following is an example of a design using the above approach:

INPUT

Primary turns (*Np*) = 1

Sensitivity (*S*) = 0.5 V/A

Series AC impedance (*Zsac*) = 0.005 O

Maximum current rating (*Imax*) = 5 A

Minimum frequency response (*fmin*) = 20 kHz

OUTPUT

Secondary turns (*Ns*) = 100

Secondary termination resistance (*Rt*) = 50 O

Minimum inductance factor (*ALmin*) = 3981 H/n2

CHOOSING A CORE

Quite often, a soft ferrite toroidal core is used for a current sense transformer. A core of surprisingly small cross section will be sufficient for current transformers handling multiple amperes at typical switch mode power frequencies. A toroidal core is well suited for a transformer with a single turn primary since it is desired to keep the primary to secondary coupling as good as possible. The toroidal core works well here because the secondary turns are completely surrounding the single primary conductor passing through the hole. Other shapes are also used, particularly at lower frequencies, where the required cross section is larger and higher numbers of both primary and secondary turns are used.

As seen in the equivalent circuit in Figure 1, the primary is in shunt across the primary side series AC impedance (*Zsac*). If the primary is only one turn, the inductance factor of the core needs to be relatively large to provide sufficient inductive reactance at the low frequency end of the passband. A toroidal shape is also efficient for this reason because the magnetic path length of a small toroid can be made small relative to the cross sectional area which will yield a high inductance factor per unit volume.

A high permeability material is also desirable in achieving a high inductance factor. However, one also has to take into account the required operating temperature range of the transformer. The permeability of high permeability grade materials can drop significantly with decreasing temperature.

The required cross sectional area of the core is approached in essentially the same way as with any transformer. It is a function of the core material, the series AC impedance (*Zsac*) on the primary side, the maximum ACrms current the primary will see, and the number of primary turns.

It will first be necessary to calculate the maximum voltage (*Ep max*) that will appear across the primary.

$$E_p \max = I_p \max \cdot Z_{sac}$$

For a sinusoidal AC current with no DC component, the formula relating primary voltage (*Ep*), turns (*Np*), frequency (*f*), and cross sectional area (*Ae*) is:

$$E_p = 4.44 \cdot f \cdot N_p \cdot B_{peak} \cdot A_e \cdot 10^{-10}$$

Solving for Ae, we have:

$$A_e = \frac{E_p}{4.44 \cdot f \cdot N_p \cdot B_{peak} \cdot 10^{-10}}$$

As with any transformer, determining a suitable Bpeak is a function of core material and the maximum operating temperature of the transformer, as well as core losses. It is suggested to keep the maximum peak flux density at no more than 50% of the saturation flux density of the material at a particular temperature.

DESIGNING FOR A DC COMPONENT

As with any transformer, if the current in the circuit into which the current sense transformer will be inserted has a DC component, it must be taken into account in the transformer design. The DC component of the current in the primary will produce a DC component of flux density in the core material. An equation for calculating the approximate value of the DC component of flux density is as follows:

$$B_{dc} peak = \mu_e \cdot H_{dc} peak$$

Where,

$$H_{dc} = \frac{4\pi \cdot N_p \cdot I_{dc} peak}{l_e}$$

The units are B in gauss, I in amperes, le (the magnetic path length of the core) in mm, and H in oersteds. This is only an approximation because the permeability of the core material will decrease as DC current increases.

The μe in the Bdc formula above is the effective permeability of the magnetic circuit of the transformer. Of course, if an ungapped toroid core is used, the effective permeability is the permeability of the material. On the plus side, usually the primary of a current sense transformer has a small number of turns. Since Hdc is proportional to turns, this is desirable. A gapped ferrite core or powdered metal core may be required for situations with high DC components.

FREQUENCY RESPONSE

As has already been discussed, the low frequency rolloff of the transformer is a function of the primary inductance. A high inductance factor core is desired because of the low number of primary turns. As the inductive reactance of the primary decreases with decreasing frequency, it will effectively shunt an excessive amount of current away from the series AC current sense impedance as frequency decreases.

As for the high frequency rolloff of a current sense transformer, there are both positives and negatives to this type of design. On the positive side, coupling between primary and secondary is usually good, so leakage inductance is relatively low. On the negative side, the turns ratio of these transformers tends to be high which causes a relatively large shunt capacitance to appear across the primary. It is the distributed capacitance of the secondary winding reflected into the primary. The reflected capacitance varies with the square of the turns ratio.

$$C_p = C_s \cdot n^2$$

The larger the value of Cp, the lower the high frequency rolloff of the transformer. It begins to shunt current away from the Zsac element as frequency goes up and reactance goes down.

TRANSIENT OR PULSE RESPONSE

The current sense transformer will respond adequately to pulse or transient type currents. Leakage inductance and shunt capacitance tend to deteriorate transient response. The leakage inductance of a toroidal unit using a high permeability core is relatively small. The shunt capacitance at the primary is not large except for very high turns ratios.

With a unipolar rectangular pulse of current applied through the primary, a unipolar rectangular voltage pulse is developed across Zsac and a calculation of the resulting flux density change (?B) in the core material can be calculated on the basis of voltage.

$$\Delta B = \frac{E_p \cdot \Delta T \cdot 10^4}{N_p \cdot A_e}$$

Where B is in gauss, Ep is in volts, T is in µs, and Ae is in mm2.

Energy is stored in the magnetic field of the transformer when the pulse is applied. If there is an off time between pulses, that magnetic field collapses and the energy is returned to the circuit. However, in the case of most current sense transformers, the very low shunt resistance makes the discharge path highly over-damped and there is no significant voltage spike during energy discharge.

CONCLUSIONS

With the ever expanding electronics universe, there will continue to be a push for the precise measuring of electric current for safety and control issues as well as a need for better device efficiency through power management solutions. Current sense transformers are essential components in these solutions. The design engineer needs to remain aware that there are many different types of CTs available using several different types of core materials from ferrite to iron powder to amorphous alloy. A simple design produce like the one demonstrated in this paper can aide in the design process and increase the speed at which new solutions are brought to the marketplace.

PARALLEL OPERATION OF TRANSFORMERS

Courtesy: ABB

ABB Small Power Transformers

This leaflet contains general procedures to be followed from the time the transformer and its accessories are received, until it is put into operation. These instructions do not purport to cover all possible contingencies that may arise during installation, operation, or maintenance, and all details and variations of this equipment.

The theoretically ideal conditions for paralleling transformers are:

Identical turn ratios and voltage ratings.

Equal percent impedances

Equal ratios of resistance to reactance

Same polarity

Same phase angle shift

Same phase rotation

Single-Phase Transformers

For single-phase transformers, only the first four conditions apply, as there is no phase rotation or phase angle shift due to voltage transformation.

If the turns ratios are not the same, a circulating current will flow even at no load. If the percent impedance or the ratios of resistance to reactance are different there will be no circulating current at no load, but the division of load between the transformers when applied will no longer be proportional to their KVA ratings.

THREE-PHASE TRANSFORMERS

The same conditions hold true for three phase transformers except that in this case the question of phase rotation and phase angle shift must be considered.

PHASE ANGLE SHIFT

Certain transformer connections as the wye-delta or wye-zigzag produce a 30º shift between the line voltages on the primary side and those on the secondary side. Transformers with these connections cannot be paralleled with other transformers not having this shift such as wye-wye, delta-delta, zigzag-delta, or zigzag-zigzag.

PHASE ROTATION

Phase rotation refers to the order in which the terminal voltages reach their maximum values. In paralleling, those terminals whose voltage maximums occur simultaneously are paired.

POWER TRANSFORMER PRACTICE

The preceding discussion covered the theoretically ideal requirements for paralleling. In actual practice, good paralleling can be accomplished although the actual transformer conditions deviate by small percentages from the theoretical ones.

Good paralleling is considered attainable when the percentage impedances of two winding transformers are within 7.5% of each other. For multi-winding and auto-transformers, the generally accepted limit is 10%.

Furthermore, in power transformers of normal design, the ratio of resistance to reactance is generally sufficiently small to make the requirement of equal ratios of negligible importance in paralleling.

When it is desired to parallel transformers having widely different impedances, reactors or auto-transformers having the proper ratio should be used. If a reactor is used, it is placed in series with the transformer whose impedance is lower. It should have a value sufficient to bring the total effective percent impedance of the transformer plus the reactor up to the value of the percent impedance of the second transformer.

When an auto-transformer is used, the relative currents supplied by each transformer are determined by the ratio of the two sections of the auto-transformer. The auto-transformer adds a voltage to the voltage drop in the transformer with the lower impedances and subtracts a voltage from the voltage drop in the transformer with the higher impedance. Auto-transformers for use in paralleling power transformers are specially designed for each installation. The wiring diagram showing the method of connecting the auto-transformer is usually furnished.

In general, transformers built to the same manufacturing specifications as indicated by the nameplate may be operated in parallel.

Connecting transformers in parallel when the low voltage tension is comparatively low requires care that the corresponding connecting bars or conductors have approximately the same impedance. If they do not, the currents will not divide properly.

CAPACITOR VOLTAGE TRANSFORMERS (CVTS)

Courtesy: Ritz Instrument Transformer

TYPE

Capacitor voltage transformers are for measuring and protection purposes. In addition CVTs can be equipped with carrier accessories to allow carrier line coupling (PLC: Power line coupling) to high-voltage lines for high-frequency data transmission: CCVTs.

DESIGN

The CVT consists of two main parts: an inductive circuit housed in the base tank and one or more insulators containing series connected capacitor elements mounted on top of the base tank.

Type OTCF 245

CAPACITOR ELEMENTS (INNER INSULATION)

Capacitor elements are wound from alternate layers of aluminum foil, polypropylene film, and kraft paper. The capacitor elements are impregnated with synthetic oil distinguished for its gas absorbing qualities. Precisely controlled vacuum and temperature treatments removes gas and moisture from the paper and oil, resulting in an insulation structure of the highest integrity.

INDUCTIVE ELEMENT

The inductive element steps down the intermediate voltage provided by the capacitor elements to values suitable for relaying and metering purposes. The inductive element is housed in a die cast aluminum base tank with a die cast aluminum cover eliminating the need for painting.

INSULATOR (OUTER INSULATION)

The outer insulation consists of high-quality aluminum oxide porcelain in brown or grey according to RAL 8016 or ANSI 70 respectively (ceramic material at least C 120 according to IEC 672). Standard creepage distances are available according to the dimension tables. Larger creepage distances are available on request. Connecting flanges made of hot-dip galvanized grey cast iron are bonded to the insulator by means of Portland cement. Upon request, a composite insulator consisting of a fibre glass reinforced tube and silicone rubber sheds can be provided as an alternative to porcelain.

HOUSING

Capacitor units are mechanically coupled together by means of stainless steel hardware passing through the corrosion proof cast aluminum expansion housing. The mechanical connection also establishes the electrical connection between capacitor units. This facilitates field assembly of the CVT.

SEALS

The capacitor elements have oil-resistant silicone rubber double gaskets. Single piece moulded O-ring type gaskets are used for all other sealing points.

HERMETIC SEALING SYSTEM

Each capacitor unit is hermetically sealed. A stainless steel diaphragm (expansion bellows) is installed to preserve the integrity of the oil by maintaining the hermetic seal while allowing for thermal expansion and contracting of the oil. The capacitor units operate in a practically pressure-free mode over a very *Expansion body* wide ambient temperature range. The base tank is filled with degassed purified mineral oil and hermetically sealed from the environment and from the synthetic oil in the capacitor units. A sight glass at the rear of the tank provides for easy monitoring of the oil level. No oil maintenance is necessary throughout the service life of the unit. An oil sampling valve is provided on the base tank.

Expansion body

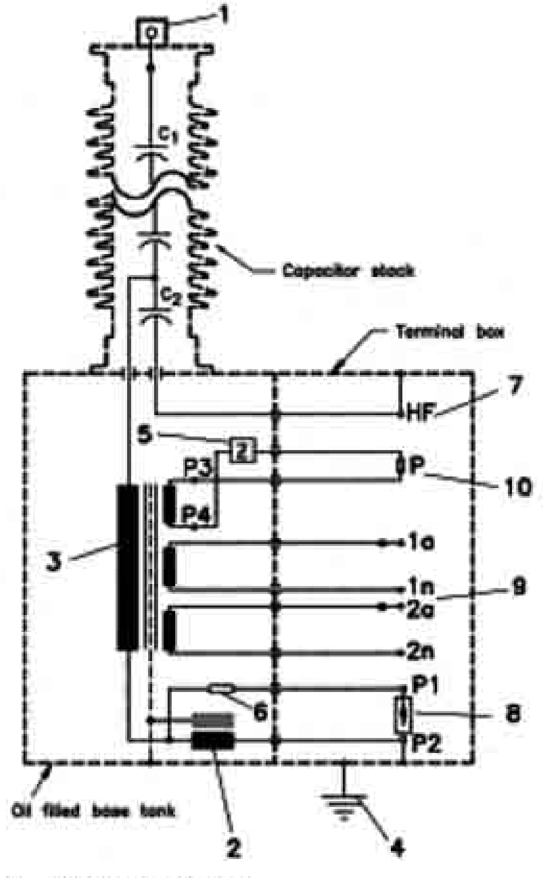
PRIMARY TERMINAL

Several variations are available to meet customer requirements: a vertical palm of aluminum alloy with the specified hole pattern, a line trap mounting adapter with removable HV terminal, or vertical stems of aluminum alloy of the specified diameter. Any of the terminals may be nickel or tin plated solid copper.

SECONDARY TERMINAL BOX

The terminal box is very spacious to accommodate all required connections. The secondaries of the inductive circuit (EMU: electro magnetic unit) are brought out of the base tank through an oil/air seal block assembly. Secondary terminals are housed in a secondary terminal box accessible by a large lockable door. The secondary terminal box area is warmed by heat transfer from the oil filled box. This prevents condensation in the terminal box and removes the need for a space heater. An aluminum gland plate is provided to accommodate customer conduit hubs. Terminal box protection is IP 54 according to IEC 529.

PRINCIPLE CIRCUIT DIAGRAM



1. *High-voltage terminal*
2. *Compensation reactor*
3. *MV voltage transformer*
4. *Ground terminal*
5. *Ferroresonance suppression device*
6. *Damping resistor*
7. *Carrier (HF) terminal at CCVTs (optional)*
8. *Overvoltage protective device*
9. *Secondary terminals*
10. *Link, to be opened for test purposes*

SECONDARY WINDINGS

To meet the requirements for measuring and protection, generally two secondary windings are provided with an option of up to four windings, including the earth fault winding. The maximum burdens are shown in the table on the next page.

CARRIER ACCESSORIES - FOR COUPLING CAPACITOR VOLTAGE TRANSFORMER (CCVT)

The CCVT is equipped with carrier accessories for PLC service. An external carrier grounding switch (CGS) and carrier entrance bushing are provided in the terminal box. The carrier accessories include a carrier drain coil with protective spark gap. The drain coil and a protective spark gap are installed in the base tank when a potential ground switch (PGS) is provided to prevent the loss of the carrier signal when the PGS is in closed position.

CORROSION PROTECTION

The CVT is maintenance free and does not require painting. All metallic parts are corrosion-proof: housings are of sea-water-resistant aluminum alloy and porcelain fittings of hot-dip galvanized iron. All hardware is hot dip galvanized or stainless steel. On request, a coat of paint with a two components paint system is provided. e.g. RAL 7033 (green-grey), ANSI C 70 (light grey) or to customer specification.

SERVICE LIFE

No routine maintenance of the unit or oil sampling is required. CVTs require only a normal cleaning program for external surfaces. This, combined with the corrosion resistance of all metal parts, should yield a trouble free service life of more than 30 years.

RATING PLATE

Each transformer is provided with a name plate of metallically anodized weatherproof aluminum or etched stainless steel.

GROUNDING

Each transformer is provided with two grounding terminals with two or four 14mm diameter holes. One grounding pad is located at each side of the unit.

FREQUENCY

50 Hz or 60 Hz, other values on request.

DIELECTRIC LOSS FACTOR / TAN _

Less than 0.06 % / 0.0006 at rated voltage

Less than 0.08 % / 0.0008 at power frequency test voltage

RADIO INFLUENCE VOLTAGE (RIV)

Less than 2500 μV at 1.1 Um

PARTIAL DISCHARGES

For the capacitor units, the partial discharge intensity is less than 5 pC at 1.2 times maximum line-to-ground voltage and less than 10 pC at twice the rated voltage after the power frequency voltage test.

AMBIENT TEMPERATURE

-30°C … +35°C (24h average).
Other values are possible on request,
e.g. -50°C … +50°C.

SEISMIC WITHSTAND CAPABILITY

0.5g up to type OTCF 245…
0.25g from type OTCF 362…
Higher value is possible on request.

SPECIFICATIONS

RITZ manufactures according to all national and international standards, such as AS, CAN/CSA, IEC, IEEE, NBN, NEN, ÖVE, SEN, UTE, VDE and, on request, according to customers' special requirements.

TEST SECTIONAL DRAWING

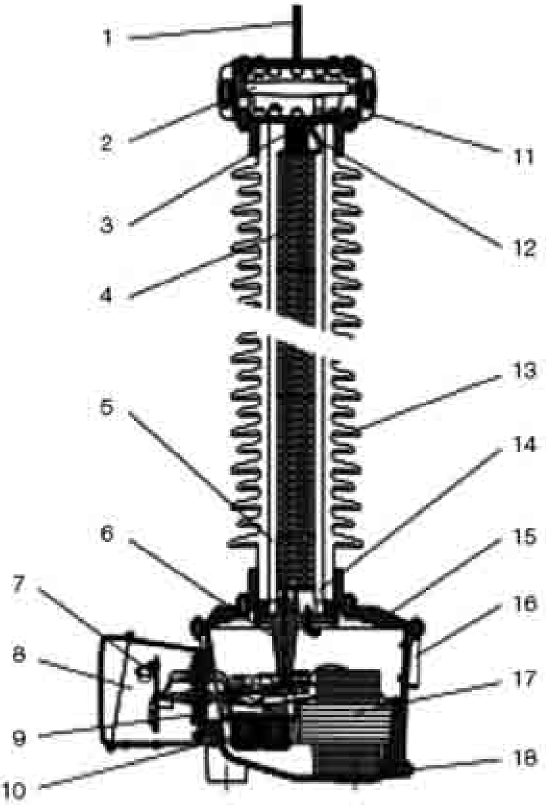
Routine tests are performed in accordance with national and international standards. Each Ritz capacitor element is routine tested for lightning impulse, power-frequency withstand, partial discharge, dielectric loss factor and capacitance. A test report is provided for each unit.

TRANSPORT

CVTs must be transported and stored in upright position. Multi-capacitor unit assemblies are delivered with the upper capacitor units packed in the same crate.

INSTALLATION

The base unit and upper stack elements can easily be assembled by following the instruction manual. No special tools are required.

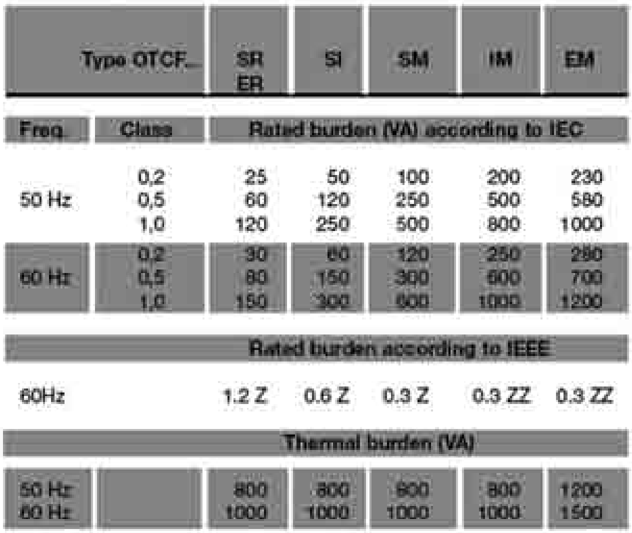


1. Primary terminal 11. Diaphragm housing
2. Oil expansion diaphragm 12. HV lead of capacitor
3. Spring assembly 13. Porcelain insulator
4. Capacitor stack 14. LV lead of capacitor
5. Intermediate voltage lead 15. Cover plate
6. Bushing assembly 16. Sight glass
7. Reactance protective gap oil level indicator
8. Secondary terminal box 17. Transformer
9. Seal block assembly 18. Oil sampling device
10. Reactance

RATINGS

Capacitive voltage transformers can be rated for metering and/or protection purposes.

The following burdens (as a sum of all windings except the ground fault winding) can be achieved



	Type OTCF…	SR ER	SI	SM	IM	EM
Freq.	Class	Rated burden (VA) according to IEC				
50 Hz	0,2	25	50	100	200	230
	0,5	60	120	250	500	580
	1,0	120	250	500	800	1000
60 Hz	0,2	30	60	120	250	280
	0,5	80	150	300	600	700
	1,0	150	300	600	1000	1200
Rated burden according to IEEE						
60Hz		1.2 Z	0.6 Z	0.3 Z	0.3 ZZ	0.3 ZZ
Thermal burden (VA)						
50 Hz		800	800	800	800	1200
60 Hz		1000	1000	1000	1000	1500

DETECTION OF PARTIAL DISCHARGE IN CAST-RESIN DRY-TYPE TRANSFORMER BY USING ACOUSTIC EMISSION TECHNIQUE

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Abstract: With a view to providing a stable electric quality, it is very important for industries to maintain their electronic equipment and to predict and diagnose their failures. Cast-resin dry-type transformers are humidity-proof, low-noise, inflammable and not harmful to the environment, so they are widely used in hospitals, high-tech companies, MRT systems and the aircraft industry. In order to increase the transmission efficiency of power line, Taiwan Power Company, therefore, raises the voltage to a higher level. The insulation in the transformer will then sustain more electrical stress.

The cause of transformer failure is mostly due to partial discharge (PD) caused by the worsening of insulation. If there is no correct diagnosis in time, the cast-resin dry-type transformer will be stricken due to the breakdowns of insulating resin in the high-tension coil. Although the situation will not cause an explosion, it will stop production lines and result in huge losses to the company. In this paper, the acoustic emission (AE) method was used to analyze the signals of PD in cast-resin dry-type transformers. First, to find the power-density spectrum of PD, we chose a 150 kHz resonant type AE sensor (VS150-M). Experiments showed that besides the 148 kHz, there was another signal in lower frequency. We then used a wide-band type sensor (Fuji 2045S, 200 kHz ~ 2.5 MHz), and found three main frequencies at 60, 90 and 160 kHz. Finally, we used a low-frequency type sensor (VS30-V, 23~80 kHz), trying to find the actual power-density spectrum of the PD signal.

The research showed that after passing the 40-dB preamplifier, the signal amplitude was about 200 mV (peak-to-peak); power-density spectrum is between 40 kHz and 60 kHz. But, 52 kHz is considered to be the lowest frequency of PD. This research aimed to establish a simple and convenient on-line diagnostic method for cast-resin dry-type transformers by AE technique.

Introduction: Usually, there are two ways to detect partial discharge in cast-resin dry-type transformers.

1. Electrical Research Association (ERA). Partial discharge pulse current can be detected from the detection circuit. This method is easy for quantitative measurements and has high sensitivity. It is standardized by IEC (International Electrotechnical commission) to detect electric charge of partial discharge pulse current, using pico-coulomb (pC) as a unit. But there are three main disadvantages. First, because of its high sensitivity in measurement, false alarms are also high. Secondly, this method puts focus on the ground connection of transformers which will produce electric current if the transformers have partial discharge. The maintenance of equipment cannot be performed because it is hard to distinguish which high-tension coil is partially discharged. Thirdly, this method is not suitable for long-term monitoring of transformers. It is too costly to connect measurement equipment to ground lines.

2. Non-electric approaches. They include acoustics, phonology and observing discharge effects of the objects tested. These approaches are not used in quantitative measurements but in recognizing the position of partial discharge. There are two types of acoustics approach: contact and non-contact. Taiwan Electric Research and Testing Center has used the latter for many years with significant results [1], while the AE technique used in our research belongs in the contact category. Our research used a contact-type AE sensor.This method has several advantages:

1. AE sensors can be attached to three different high-tension coils. By observing and analyzing signals collected by sensors, the researchers can find the right high-tension coil that puts forth partial discharge, and further maintenance can then be performed.

2. Acoustic signals will occur only when the partial discharge reaches a certain intensity. Unlike the ERA method, it does not have a high sensitivity or suffer from high mistaken rates.

3. This method is suitable to monitor transformers for long time and therefore the cost is reduced.

According to Tian's [2] discharge experiments with the polymeric insulation model, AE sensors are attached to polymeric insulation to collect acoustic signals. Then, impedance, coupling capacitor and the detecting equipment for partial discharge are used to collect electrical signals. There is a void in the middle of the polymeric insulation sample which is shaped like a sandwich. A high-voltage probe is attached above the void and another below the void. Finally, discharge occurs as a result of raising the electrical voltage on probes.

The purpose of these experiments is to find out the relationship between acoustic signals and electrical signals from the void. The conclusion is that acoustic signals and electrical signals from the void are absolutely related and the strength of discharge influences the intensity of acoustic signals. In other words, only when the discharge reaches a certain intensity do acoustic signals occur.

The 150 kHz sensors used in the above experiments are resonant type sensors whose main feature is that any tiny signal which occurs near 150 kHz will be strongly amplified because of resonance effect. But the amplification in other different frequencies varies significantly; that is, the result is not the actual frequency spectrum. Take the reflection chart of Vallen™ VS150-M for example(Fig. 1). The sensitivity in 150 kHz is at least 7 dB higher than that in 100 kHz. However, we can see the main frequency is not in 150 kHz but in 100 kHz.

Therefore, the main disadvantage of using resonant type sensors is that the signals measured are not the real ones. Becausefor this reason, the purpose of our research is to find out the real frequency spectrum of signals.

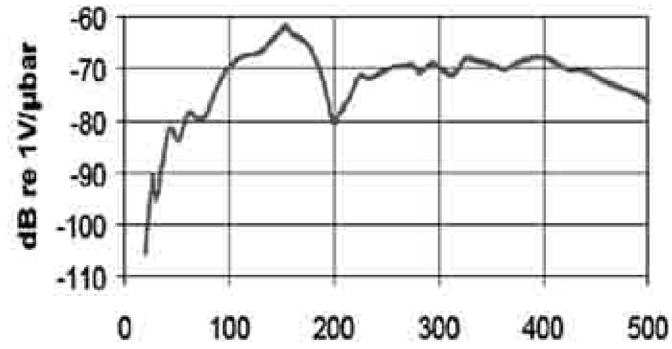


Fig. 1. Frequency spectrum of the VS150-M (kHz) AE probe [3].

Research Method: Partial discharge is similar to the phenomenon of pulse, which causes mechanical pressure waves in the material itself as the radiation of sound does. When the collision of molecules happens in the inner part of one material and its neighboring structure, a sound source is formed which will radiate sound wave. The sound wave causes propagation everywhere in the inner part of equipment. And in the AE method, AE sensors are closely attached to the surface of the equipment. The piezoelectric material in the AE sensors will transform the mechanic pressure wave into electrical acoustic signals, as shown in Fig. 2.

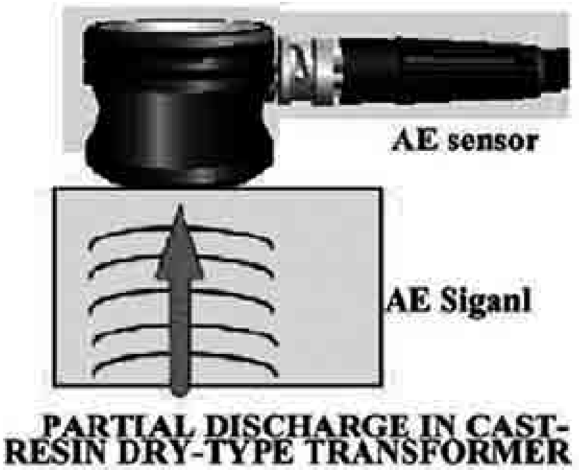


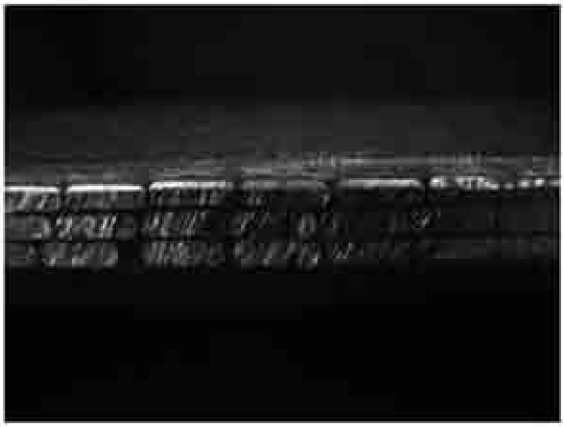
Fig. 2. The sensors – converting the mechanical wave into an electrical AE signal.

First, accompanied with the preamplifier (AEP4: 5 kHz ~ 3.8 MHz) is Vallen ^{V}S150-M, a 150 kHz resonant sensor commonly used in industry. The result is that the general wave is the same as in the ordinary experiment, which should be compared with the following experiments. Second, accompanied with the preamplifier is ValIenTM Fuji 2045S, a wide-band type sensor. This sensor is used to analyze higher frequency spectrums. Because resonant sensors often create the confusion that signals appear in the frequency of 150 kHz, wide-band type sensors can detect real signals. This experiment can detect if higher-frequency signals are present. Finally, a ValIenTM VS30-V AE sensor is used for two reasons. (1) VS30-V, a low-frequency type sensor, has a flat frequency response between 23 kHz and 80 kHz. Hopefully the real frequency spectrum of PD signals can be found. (2) VS30-V has high sensitivity, and thus can be applied to find the most detailed signals in low frequency.

The following will discuss the energy transmission and reflection of sound waves in the inner part of high tension coil. Figure 3(a) shows the cross section of a partial high tension coil. Figure 3(b) shows the cross section of glass fiber in the resin of high tension coil. High tension coil consists of copper wires which are arranged layer by layer. In order to simplify the analysis, the hypothesis is made that the coil is a complete brass block and next to the brass block is a pure piece of resin. According to the relation among acoustic impedance (Z), material density (_) and sound velocity (V) [5]: $Z = r V$

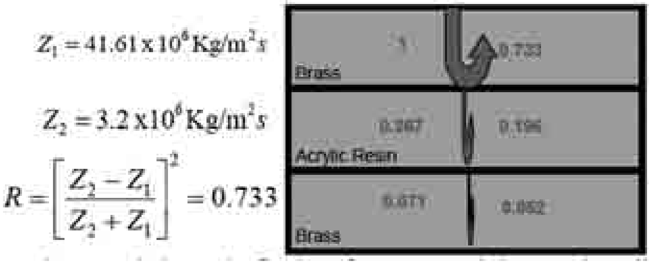
The acoustic impedance of brass is $Z_1 = 41.61x10^6$ Kg/m^{2}s, and the acoustic impedance of resin, glass fiber not contained, equals to $Z_2 = 3.2x10^6$ Kg/m^{2}s.

When sound is transmitted between two materials, their acoustic impedances have a determined influence on the transmission coefficient and reflection coefficient of sound wave power in passing through the interfaces. Figure 4 shows the attenuation of sound wave in brass and resin. First, assuming that the initial power of sound wave in the brass block equals 1, there is 26.7% of power passing through the resin and 73.3% of power reflecting back to the brass. Then, when sound wave continues to move from the resin to the bottom layer of brass, only 7.1% of power passes through the second layer of brass and 19.6% of power reflects back to the resin. Therefore, the transmission of sound in the inner part of high tension coil is very difficult.



(a)

Fig. 3. (a) The cross section of partial high tension coil. (b) The cross section of glass fiber in high tension coil.



$$Z_1 = 41.61 \times 10^6 \mathrm{Kg/m^2 s}$$

$$Z_2 = 3.2 \times 10^6 \mathrm{Kg/m^2 s}$$

$$R = \left[\frac{Z_2 - Z_1}{Z_2 + Z_1}\right]^2 = 0.733$$

Fig. 4. The transmission and reflection of power wave in brass and acrylic resin.

The resin used in the above model is pure resin, which breaks down easily with the change of temperature. Most manufacturers add quartz sand or glass fiber to the resin in order to increase its mechanical strength. Hence, its acoustic impedance will differ from that of pure resin. Glass fiber increases the strength of resin and, at the same time it attenuates the intensity of sound wave. Thus, it is more difficult for sound wave to transmit in genuine high tension coils. Therefore, AE sensors, which have higher sensitivity, should be used to measure sound wave signals.

Experiment: The cast-resin dry-type transformer used in this experiment has the following standard. Capability: 10 kVA. Primary coil electrical voltage: 12 kV. Secondary coil voltage: 120 V. The procedure for this experiment is as follows. First, a three-phase auto transformer is connected to the secondary coil of the cast-resin dry-type transformer. Next, the output of the auto transformer is adjusted in order to let the primary coil induce the electrical voltage. And after an AE sensor is applied to the high tension coil of the cast-resin dry-type transformer, the filter is used to filter noise and electromagnetic interference. Then, through the preamplifier (AEP3), the signal will be amplified (gain: 40 dB). Finally, the digital oscilloscope LeCroy™ LT354 is used to acquire the AE signals. Meanwhile, the spectrum analysis will be quickly completed with the FFT function of the scope. Figure 5 shows the basic block diagram of the measurement system. Figures 1, 6 and 7 show the frequency response of the sensors VS150-M, Fuji 2045S and VS30-V respectively.

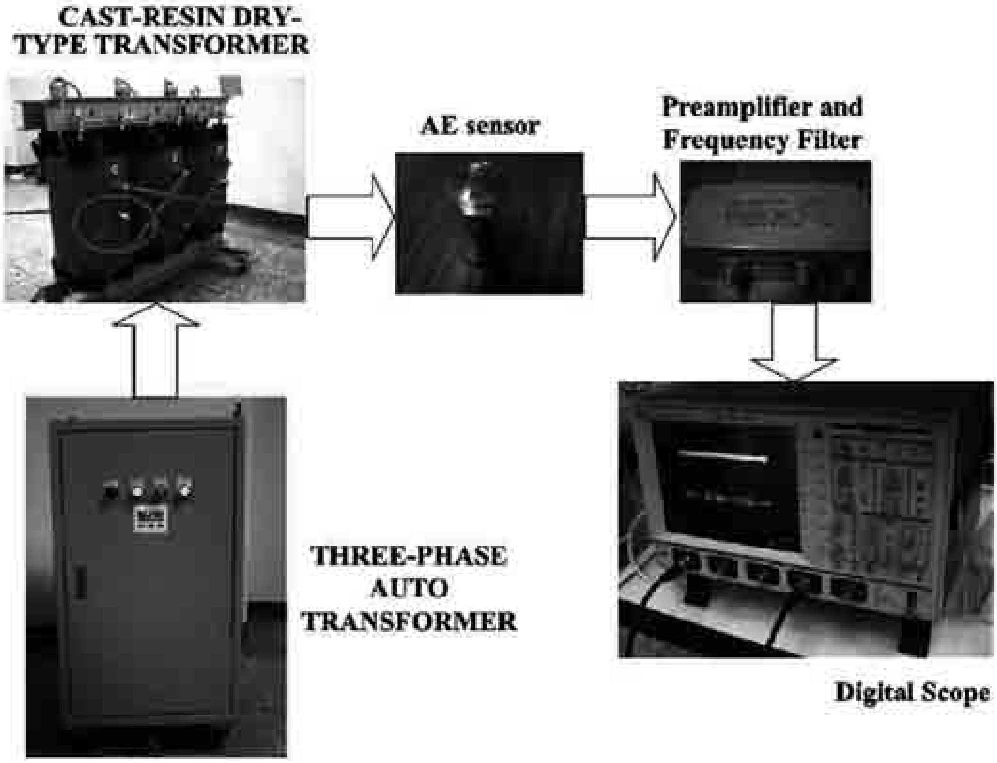

CAST-RESIN DRY-TYPE TRANSFORMER
AE sensor
Preamplifier and Frequency Filter
THREE-PHASE AUTO TRANSFORMER
Digital Scope

Fig. 5. Schematic diagram of the PD measurement system.

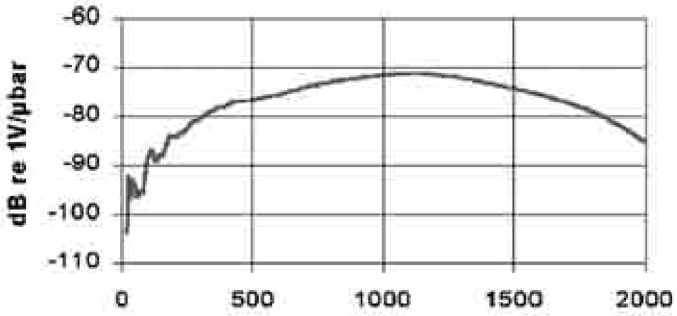


Fig. 6. Fuji 2045S, f(kHz) [3]

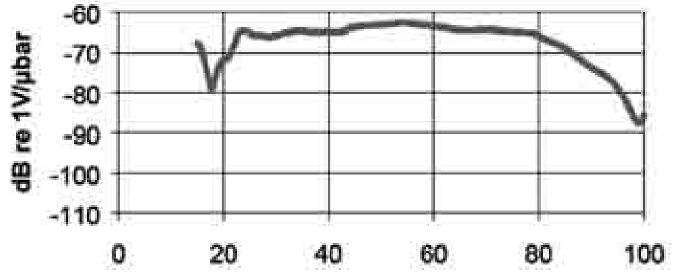


Fig. 7. VS30-V, f(kHz) [3].

Results and Discussion: As shown in Fig. 8, the AE signals detected by VS150-M along with the preamplifier (AEP4), the dominant frequency is 148 kHz. As can be seen, another frequency appears near 50 kHz. But the resonant type sensor performs badly around the 50 kHz frequency, as shown in Fig. 1. In addition, the sensitivity in 150 kHz is about -63 dB, while in 50 kHz it is about -83 dB. Their difference in sensitivity is 20 dB (ten times). So, the signal appearing in 50 kHz should be amplified ten times, which means the lower frequency AE sensor should be used to look for lower frequency signals. Signals in high frequency (> 300 kHz) are much weaker.

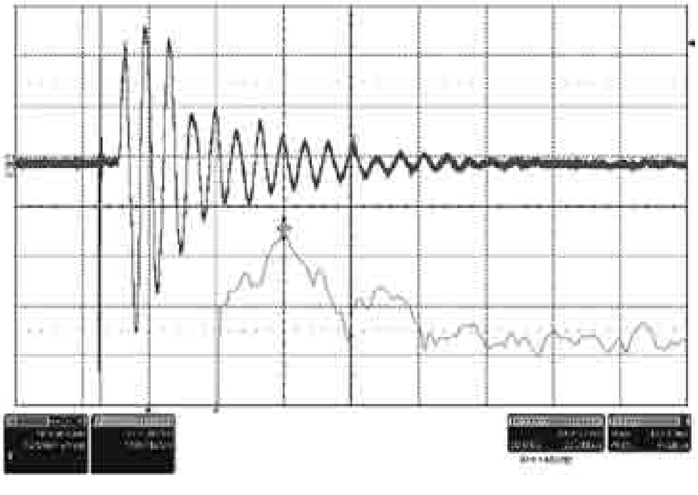


Fig. 8. AE signal and frequency spectrum that measured by using VS150-M.

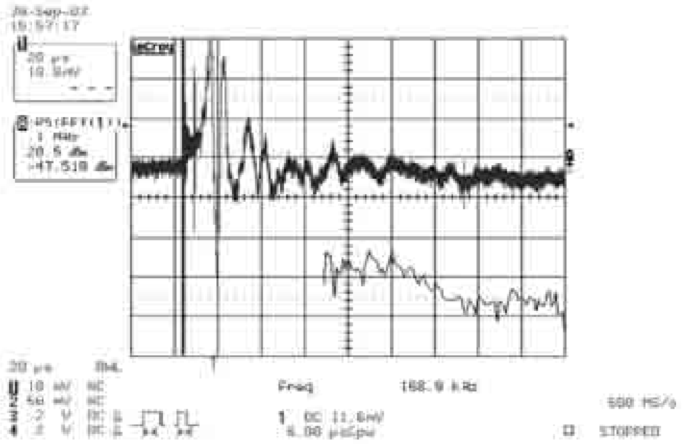


Fig. 9. AE signal and frequency spectrum that measured by using Fuji 2045S.

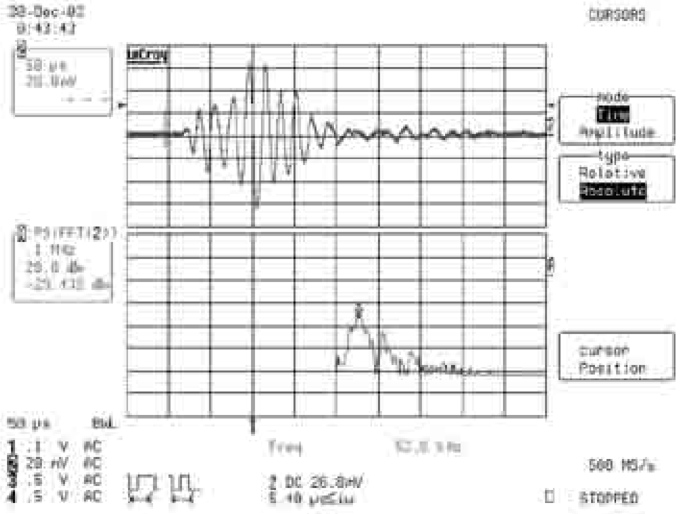


Fig. 10. AE signal and frequency spectrum that measured by using VS30-V.

Figure 9 shows the waveform measured by Fuji 2045S along with a preamplifier (AEP4). Three dominant frequencies, 60 kHz, 90 kHz and 160 kHz were found. Because there is still a signal in 60 kHz, the real signal should be bigger. In contrast, there is no signal in high frequency. From the above two results, the finding is as follows: there is definitely no signal in frequencies higher than 300 kHz, while in low frequencies between 50 kHz and 60 kHz there is definitely some signal. Therefore, lower frequency sensors should be used to measure PD signals.

Figure 10 shows the AE signal measured by VS30-V. Its dominant frequency is 52 kHz, which means the actual location of acoustic signal frequency in the cast-resin dry-type transformer is around 52 kHz. The spectrum of VS30-V between 23 kHz and 80 kHz is very flat, as shown in Fig. 7. Because VS30-V is a low frequency sensor, it will receive the audio frequency signal lower than 20 kHz. So, in measuring the real signals, a preamplifier (AEP 3) and a filter should be used in order to reject an audio signal lower than 20 kHz. The passband of the filter is from 30 to 300 kHz. In the time-domain waveform, no noise of high frequency is observed. In frequency-domain waveform, the frequency not between 30 kHz and 300 kHz is filtered out. As shown in Figs. 9 and 10, a large inductive interference of high frequency appears which will affect the reception of acoustic signals. Filters can minimize the interference.

Conclusions: We have tried using three different AE sensors to detect PD signals in cast-resin dry-type transformers. We first used the 150 kHz resonant type sensor. Then a 200 kHz ~ 2.5 MHz wide-band sensor was used there is no frequency higher than 300 kHz, but there is a low-frequency signal in 60 kHz. Finally, a 23 ~ 80 kHz low-frequency sensor was used. As a result, it was found that near 52 kHz exists the real PD signal. It was concluded that the acoustic signal of partial discharge mainly appears at 52 kHz.

The insulation materials of high-tension coil have great influence on the transmission of sound wave. Therefore, the inner structure and materials of high-tension coil will influence the production of partial discharge. In regards to material, some of the resin with quart sand or glass fiber had a great influence on the transmission of sound wave.

The filter is necessary because a high frequency induced signal appears when using the 150 kHz resonant-type sensor and the 200 kHz ~ 2.5 MHz wide band-type sensor. From a sequence of experiments, the filter is set between 30 kHz ~ 300 kHz in order to eliminate unnecessary noise and keep only the desirable signals

Acknowledgements: This work was supported by the National Science Council, Taiwan, R.O.C. under contract No. NSC 92-2622-E-006-142.

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GUIDE FOR OPTIMUM SPECIFICATION OF TOROIDAL TRANSFORMERS

BICRON Electronics Company

COST SAVING ADVANTAGES

LOWER OFF-LOAD POWER CONSUMPTION

Lower off-load power consumption leads to long term cost savings due to increased electrical efficiency. The efficiency or losses at each point in the whole system determines the overall system operating cost. Each point of conversion has losses. Minimizing these losses lowers the cost of product and provides long term cost savings to your customer. (Fig.1)

SMALLER AND LIGHTER

High packing density and related advantages lead to reduced design costs. A physically smaller transformer is less expensive to manufacture, and will also reduce your overall system cost by allowing for smaller packaging (Fig.2)

A smaller transformer also means lighter weight, which will save you costs by reducing the structural chassis design, and improving portability (Fig.3)

WIDER CHOICE OF CONFIGURATION

Selecting a transformer core designed from a single strip of steel will save cost by providing you the option of an infinite variety of configurations. This advantage leads to custom transformer dimensions to meet almost any product or system parameter.

LOW RADIATED EMI

Selecting a transformer exhibiting low radiated EMI will save costs by significantly reducing interference and shielding between the transformer and sensitive electronic components. (Fig. 4)

VIRTUALLY NO AUDIBLE NOISE

Selecting a transformer inherently void of low frequency audible noise will save costs by simplifying installation and improving the quality of the product.

SAFETY RECOGNITION

Installation of a safety agency's listed or recognized transformer, or certification of compliance, can help save costs incurred in the regulatory approval process. Typical safety agency approvals and standards applied to Bicron transformer products include UL,CSA,VDE, TUV, and IEC.

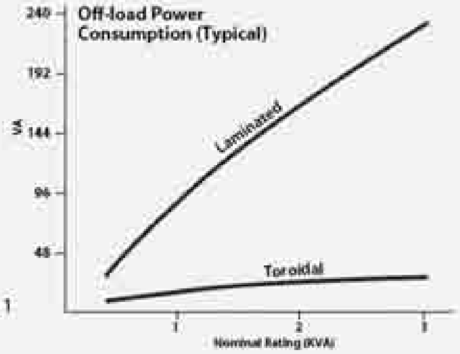


Fig. 1

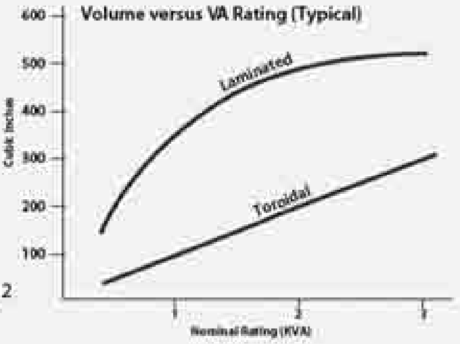


Fig. 2

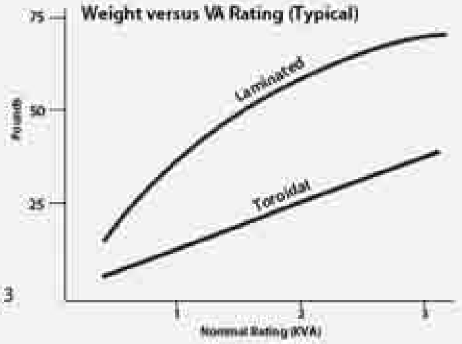


Fig. 3

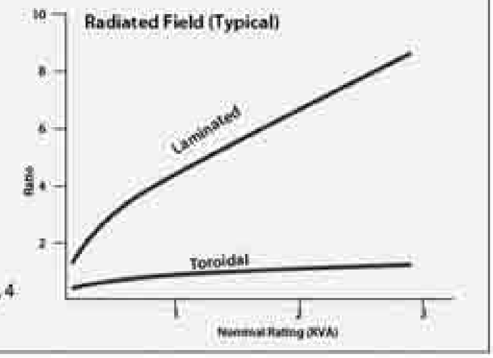


Fig. 4

TRANSFORMER FUNDAMENTALS TRANSFORMER EFFICIENCY

All transformer windings and transformer cores produce copper and magnetic losses that appear as heat:

$$VA_{in} = VA_{out} + W_{loss}$$

where $VA = \text{volts} \times \text{amperes}$

$$W_{loss} = W_{cu} + W_{fe}$$

W_{cu} = watts dissipated through copper losses in the windings

W_{fe} = watts dissipated through magnetic losses in the core

The toroidal transformer typically requires only 10% of the magnetizing current required by laminated transformers. Higher flux densities are permitted because the direction of the magnetic flux is the same as the steel core grain. High flux densities allow fewer turns of copper wire, reducing the DCR of the winding. Figure 5 shows the efficiency that can be expected in terms of VA power ratio.

HIGH PACKING DENSITY

Toroidal transformer cores are the ideal shape, which minimizes the amount of core material and allows symmetrical distribution of the winding around the entire core. This, along with higher operating flux densities, permit fewer copper wires turns than required on an equivalent laminated core. These inherent characteristics result in considerable weight and volume savings, as well as other advantages.

Referring to Faraday's equation for induced voltage in a transformer winding:

$$ERMS = 4.44 \times N \times AC \times F \times B \times 10^{-8}$$

where:

F = frequency

N = number of turns

B = flux density (gauss)

AC = core cross section area (cm^2)

Toroidal transformers can operate at flux densities up to 16.5 kilogauss, approximately 40% higher than the conventional laminated power transformer. Operation of any core beyond its maximum rated flux density will result in increased Wfe losses in addition to waveform distortion.

The weight of a transformer is comprised of the following items:

(1) Copper (windings)

(2) Steel (core)

(3) Insulation materials

(4) Mounting hardware or potting material

The obvious trade-off for weight reduction is between the amount of copper wire and the size of the core. A well-designed transformer will be a balance of copper and steel needed to obtain reasonable AC regulation, temperature rise, and minimum physical size. See Fig. 3 for a comparison of Toroidal vs.Laminated weights.

The physical dimensions (volume) of a transformer can be varied for any given design. The core of the toroid transformer is made of a strip of grain oriented silicon steel. The strip width determines the heights of the core while the inside and outside diameters determine the physical dimensions and the cores' cross-section area. The cost to produce a custom vs. standard toroid core is relatively low. Most toroidal transformers have a diameter to height ratio of 3:1, but ratios of 2:1 (high profile) and 7:1 (low profile) are possible. See Figure 2 for a comparison of the standard Toroid vs. Laminated volumes.

OTHER ADVANTAGES OF HIGH PACKING DENSITY

EMI fields are very low because of the unique construction of the Toroid transformer. These transformers are wound on a ring shaped core, a configuration that provides maximum containment of magnetic fields. Unlike laminated transformers, toroid transformers do not have air gaps within the core. Air gaps cause a discontinuity in the magnetic path giving rise to increased radiated fields. Additionally, the even distribution of the primary winding over the secondary winding, uniformly around the entire core, ensures that the magnetic fields generated in the windings can be cancelled. Reductions of up to eight times, relative to the laminated transformer, can be expected. Further reduction is possible with a metal bellyband around the outside of the transformer, or full containment of the transformer within a steel enclosure. See figure 9.

Audible noise generated by a Toroid transformer is inherently low. The single strip of steel wound into a ring and welded at both ends is very solid and stable. The copper windings and insulation system completely envelope the core, further stabilizing the transformer and dampening the acoustical noise caused by magnetostriction phenomena.

Transformer noise can also be minimized by increasing DC ripple requirements in linear power supply applications. Low DC ripple require the transformer to deliver very large pulses of current in short periods of time. The high energy pulses further increase the magnetostriction action.

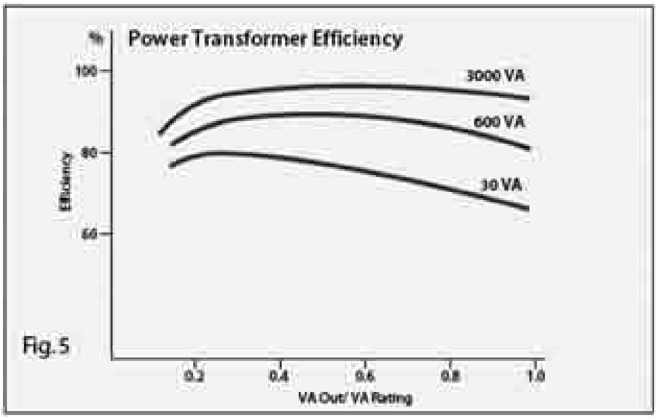


Fig.5

LINE FREQUENCY

The majority of toroidal power transformers are designed to operate in 50/60Hz, 60Hz or 400Hz applications. As the frequency increases, the thickness of the strip steel is decreased to improve efficiency. The core size and/or the winding also decreases, making for a smaller transformer. This reduction in the physical size of the transformer, as a function of frequency, should be considered when packaging a transformer in the product. A 60Hz transformer will be 20% smaller than a 50/60Hz transformer.

PRIMARY VOLTAGE

A transformer operates using magnetic induction. The basic transformer consists of two coils of wire wound on a steel core. When a voltage is applied to one of the coils, it magnetizes the core and a voltage is induced in the second coil. The ratio of the primary voltage to the secondary voltage depends on the turns ratio of the two coils:

$$V_P / V_S = T_P / T_S$$

where V _ voltage and T _turns

Taps may be provided on the transformer to compensate for different country requirements. Figure 6 shows typical primary voltage configurations.

Note: Multiple primary windings must be connected in parallel or series to maintain rated power.

SECONDARY VOLTAGE

The secondary voltage(s) of the transformer is specified with rated primary voltage and full load secondary current.

SECONDARY VOLTAGE REGULATION

The voltage regulation of the transformer is the relationship of the open circuit (no load condition) to the rated voltage (full load condition). This condition can be expressed as:

$$Reg = (V_{NL} - V_{FL}) / V_{FL}$$

where VNL = no load AC voltage and VFL = full load AC voltage

Regulation can be improved by decreasing the Wcu losses or by specifying a transformer with a larger VA rating.

SECONDARY DUTY CYCLE

The secondary VA requirements can be reduced if the load is intermittent and the "on" time is shorter than the transformer thermal time constant. Thermal time constants for transformers are typically a few minutes to fifteen minutes, depending on physical mass of the transformer.

$$Duty\ Cycle = (T_{ON} / (T_{ON} + T_{OFF})^{1/2}$$

where TON = time transformer is powering load and
TOFF = time transformer is not powering load

SECONDARY VA REQUIREMENTS

The secondary winding capacity is defined in terms of voltage, current and duty cycle:

$$VA = V_{FL} \times I_{FL} \times (Duty\ Cycle)$$

where:
VFL = AC secondary voltage at specified current requirements and
IFL = AC secondary current at specified maximum requirement

Many different primary voltage configurations are available to meet virtually any possible requirement.

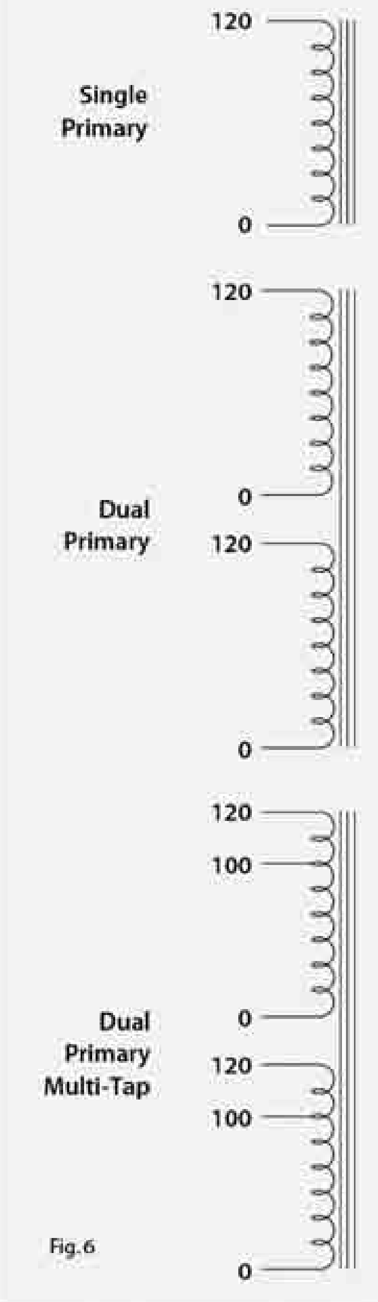
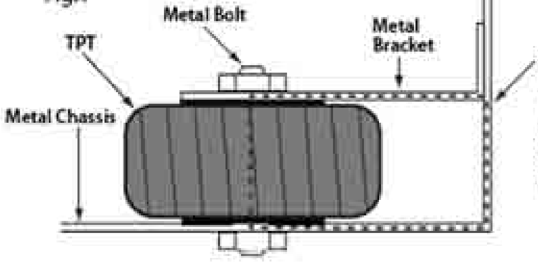


Fig.6

ELECTROSTATIC SHIELDS

There are two distinct types of transients present on the power grid; Common Mode and Transverse. Transverse noise are transients present, but not referenced to ground. Typical examples are switching power supplies, universal motors, etc. This noise is usually extinguished at its source with line filters. Common mode noise are transients present on the power grid but referenced to ground. Typical examples are lighting strikes, switching, electromagnetic pulses, etc. To decrease common mode noise, transformers can be modified by incorporating an electrostatic shield between the primary and secondary windings. The capacitance between the primary and the shield channels most of the common mode noise to ground.

Fig. 7



Shorted turn via chassis and mounting bolt.

An air gap must exist to avoid shorted turn phenomena.

THERMAL PROTECTION

There are two types of thermal protection available for transformers; Non-reset and Auto-reset. The purpose of these devices is to shut down the transformer in the event of overheating. The nonreset is used primarily for protection from internal transformer faults, tripping at a preset temperature. The auto reset provides intermittent protection from internal transformer faults and external overloads. This device will open at a preset high temperature and close at a preset lower temperature. These devices are mounted internal to the transformer and wired in series with the winding.

MOUNTING PRECAUTIONS

The inadvertent design of a shorted turn by providing a conductive loop (turn) through the center of a toroidal transformer must be avoided. This typically occurs when designing special mounting hardware for the transformer. A shorted turn results in high circulating currents, excessive heat, and poor performance. (Fig.7)

INRUSH PRECAUTIONS

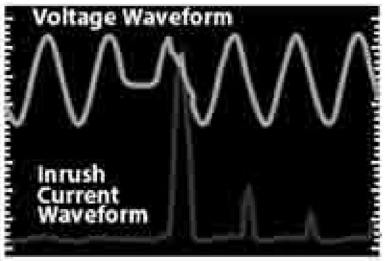
Because the core does not have air gaps, toroidal transformers have the advantage over traditional E-I transformers of low standby power consumption (magnetization current). However, this results in a higher residual flux (remanence) when power is removed. When power is reapplied the core may go into saturation, causing a current inrush which may be 15 times higher than the steady state current. The condition rarely lasts for more than two cycles as can be seen in figure 8a.

There are several approaches for addressing inrush:

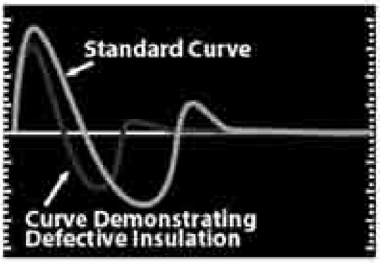
1.Adding a resistor in series with the primary winding of the transformer, which is removed from the circuit after power is applied.

2. Utilizing delayed action fuses for the protection devices.

3. Reduce the residual flux (Remanence) which will increase the magnetization current in the core. Methods used to reduce residual flux include: introducing a gap, or utilizing alternate materials and/or annealing methods.



(Fig. 8a) Primary Inrush Current Waveform, which can cause nuisance tripping of breakers, occurs when power is removed and then reapplied in the same polarity half cycle.



(Fig. 8b) Surge test waveform indicating a turn-to-turn voltage breakdown within a transformer winding.

Fig. 9

Further reduction of any radiated fields is possible with a metal bellyband around the outside of the transformer or full containment of the transformer within a steel enclosure.

TECHNICAL NOTES

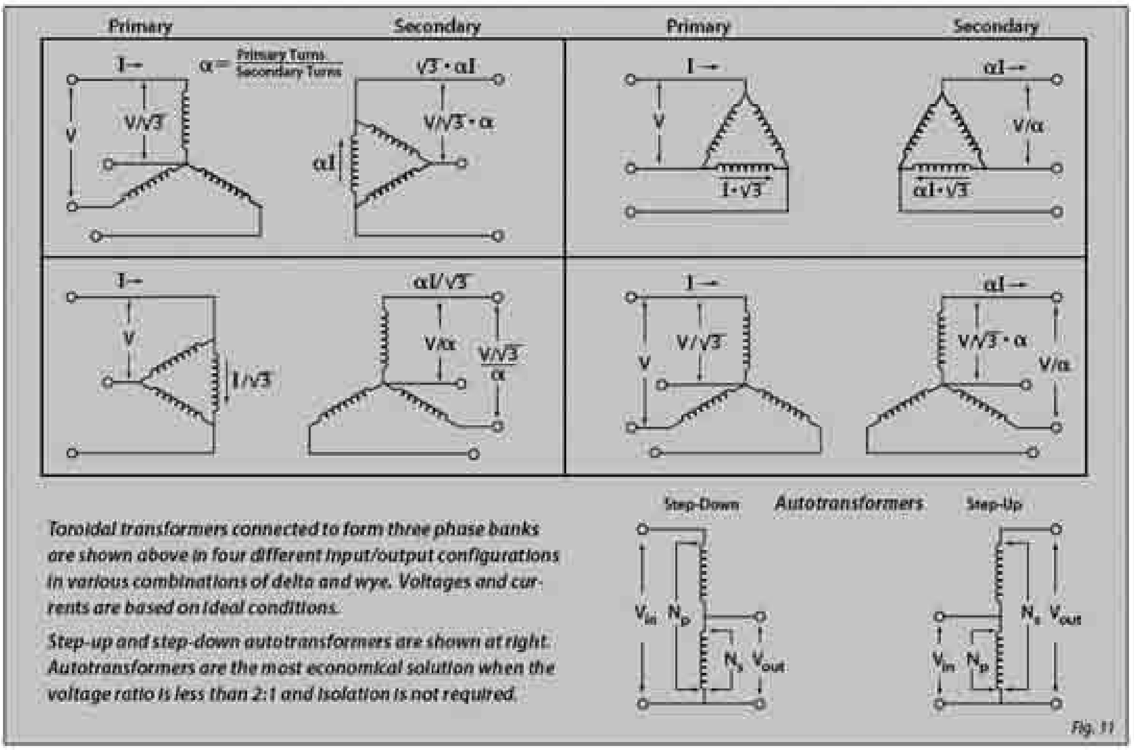
LINEAR POWER SUPPLY DESIGN

Typically there are three system configurations used in conjunction with linear power supplies. The half wave (HW), the full wave (FW), and the full wave center tap (FWCT).

Each configuration will have impact on the VA requirements of the transformer and the circuit components comprising the rectification and filtering. Please contact Bicron engineering for specific transformer parameters.

THREE PHASE SYSTEM BASICS

Three single-phase transformers may be connected to form a 3-phase bank in the configurations shown. Also shown are the voltages and currents based on ideal conditions. The VA rating of each transformer is one third the total system regardless of the selected configuration. The voltage and current ratings of each transformer is, however, configuration dependent.



Toroidal transformers connected to form three phase banks are shown above in four different input/output configurations in various combinations of delta and wye. Voltages and currents are based on ideal conditions.

Step-up and step-down autotransformers are shown at right. Autotransformers are the most economical solution when the voltage ratio is less than 2:1 and isolation is not required.

Fig. 11

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AUTOTRANSFORMER BASICS

The same transformation of voltage and current can be obtained with a single winding autotransformer as with the normal two winding transformer. There are two major differences: (1) In the autotransformer, the secondary winding is common to both the primary and secondary winding, and (2) There is a direct copper connection between the primary and secondary circuits. Autotransformers have lower leakage reactance, lower losses, smaller excitation currents, and they can be smaller and less expensive than dual winding transformers when the voltage ratio is less than 2:1. And, of course, they provide no isolation.

THERMAL CLASS

Thermal class is designated by a letter and defines the lowest temperature rating of the materials which make-up the transformer:

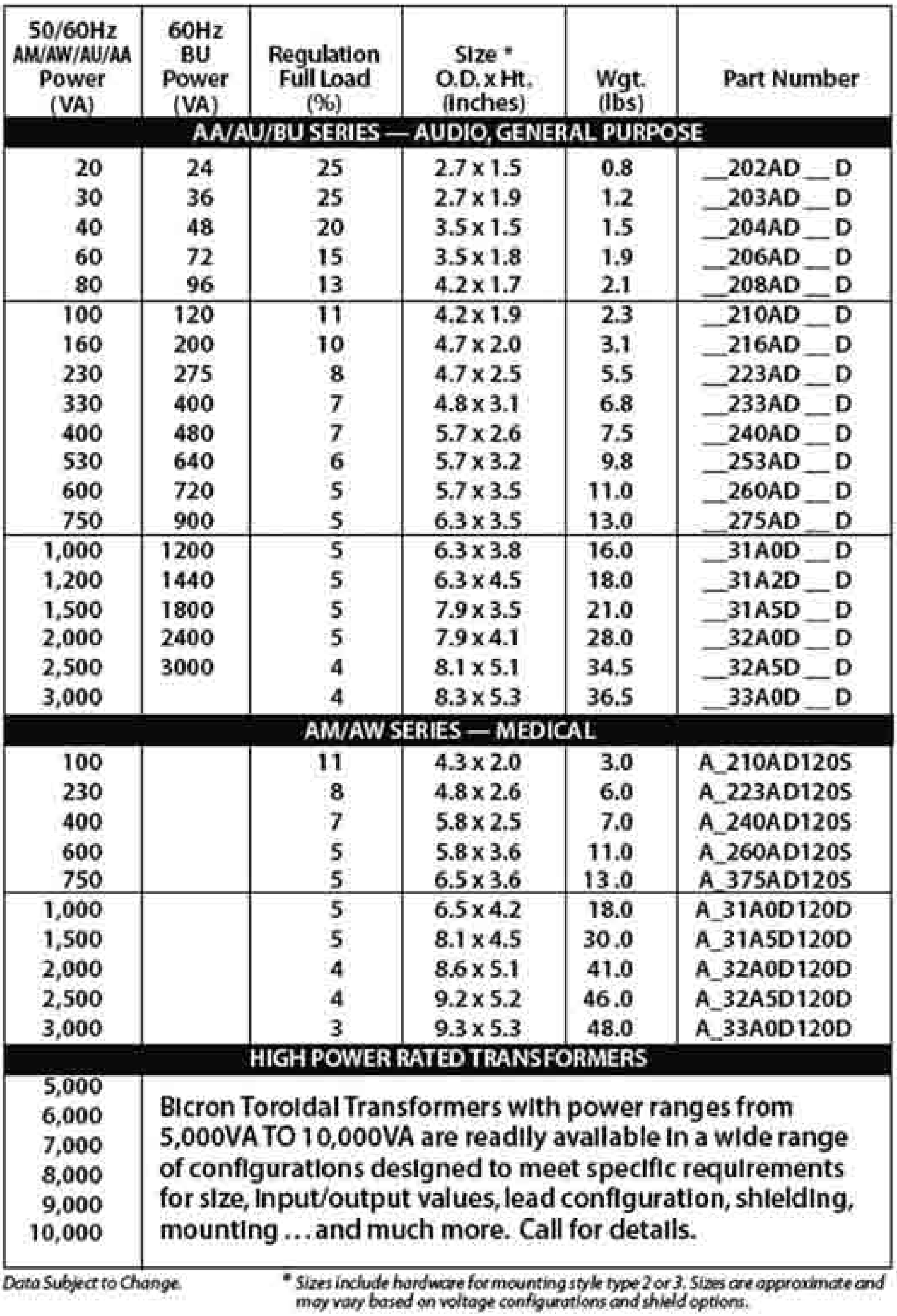
Class A materials (105°C), Class B
(130°C), Class F (155°C), Class H (180°C).

TEMPERATURE RISE

The temperature rise of a transformer can be determined by the resistance method:

$$t = ((R_2 2R_1)/R_1)3(234.52t_2)\ 2\ (t_2 2t_1)$$

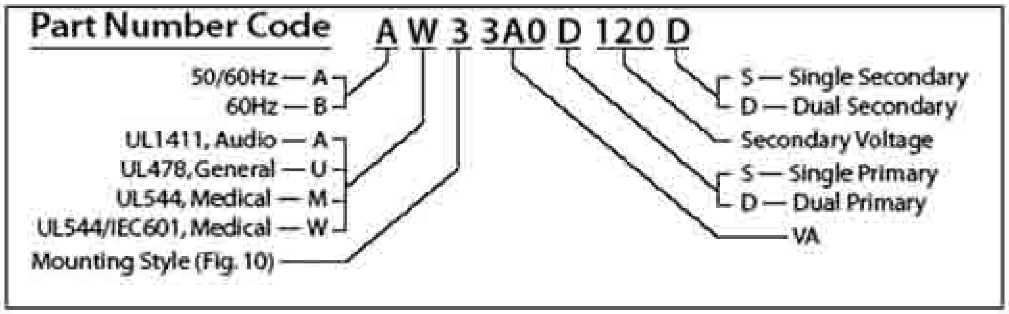
t = temperature rise over ambient,t2 (°C)
R2 = resistance of winding at end of test
R1 = resistance of winding at beginning of test
t2 = ambient temperature at end of test (°C)
t1= ambient temperature at beginning of test (°C)



50/60Hz AM/AW/AU/AA Power (VA)	60Hz BU Power (VA)	Regulation Full Load (%)	Size * O.D. x Ht. (Inches)	Wgt. (lbs)	Part Number
AA/AU/BU SERIES — AUDIO, GENERAL PURPOSE					
20	24	25	2.7 x 1.5	0.8	__202AD__D
30	36	25	2.7 x 1.9	1.2	__203AD__D
40	48	20	3.5 x 1.5	1.5	__204AD__D
60	72	15	3.5 x 1.8	1.9	__206AD__D
80	96	13	4.2 x 1.7	2.1	__208AD__D
100	120	11	4.2 x 1.9	2.3	__210AD__D
160	200	10	4.7 x 2.0	3.1	__216AD__D
230	275	8	4.7 x 2.5	5.5	__223AD__D
330	400	7	4.8 x 3.1	6.8	__233AD__D
400	480	7	5.7 x 2.6	7.5	__240AD__D
530	640	6	5.7 x 3.2	9.8	__253AD__D
600	720	5	5.7 x 3.5	11.0	__260AD__D
750	900	5	6.3 x 3.5	13.0	__275AD__D
1,000	1200	5	6.3 x 3.8	16.0	__31A0D__D
1,200	1440	5	6.3 x 4.5	18.0	__31A2D__D
1,500	1800	5	7.9 x 3.5	21.0	__31A5D__D
2,000	2400	5	7.9 x 4.1	28.0	__32A0D__D
2,500	3000	4	8.1 x 5.1	34.5	__32A5D__D
3,000		4	8.3 x 5.3	36.5	__33A0D__D
AM/AW SERIES — MEDICAL					
100		11	4.3 x 2.0	3.0	A_210AD120S
230		8	4.8 x 2.6	6.0	A_223AD120S
400		7	5.8 x 2.5	7.0	A_240AD120S
600		5	5.8 x 3.6	11.0	A_260AD120S
750		5	6.5 x 3.6	13.0	A_375AD120S
1,000		5	6.5 x 4.2	18.0	A_31A0D120D
1,500		5	8.1 x 4.5	30.0	A_31A5D120D
2,000		4	8.6 x 5.1	41.0	A_32A0D120D
2,500		4	9.2 x 5.2	46.0	A_32A5D120D
3,000		3	9.3 x 5.3	48.0	A_33A0D120D
HIGH POWER RATED TRANSFORMERS					
5,000 6,000 7,000 8,000 9,000 10,000	Bicron Toroidal Transformers with power ranges from 5,000VA TO 10,000VA are readily available in a wide range of configurations designed to meet specific requirements for size, input/output values, lead configuration, shielding, mounting . . . and much more. Call for details.				

Data Subject to Change.

** Sizes include hardware for mounting style type 2 or 3. Sizes are approximate and may vary based on voltage configurations and shield options.*



ON-LOAD TAP-CHANGERS SELECTION GUIDE

ABB Power Technology Products AB

THE SELECTION PROCESS

Below is a schematic plan, showing the selection process. Before the selection can start, certain input data has to be collected. After that the selection guide can be a help to select the most suitable tap-changer for the application in question. When the type of tap-changer is identified, the selection of the right size is made in the applicable Technical Guide. In the Technical Guide, the special features are chosen.

INPUT DATA

A number of parameters must be known prior to commencing the selection process and finally deciding type and size of on-load tap-changer.

Once the basic parameters are known and type of tap-changer has been selected, the ordering data sheets can be completed, which then defines the tap-changer and associated motor drive mechanism in detail.

If correctly chosen, the tap-changer will not restrict the occasional overloading of the transformer according to IEC 60354, ANSI/IEEE C.57.92 and CAN/CSA-C88-M90. If any other standard is required, please contact ABB.

INSULATION LEVEL

The following values occurring on all tapping positions of the transformer should be checked against the applicable technical guide.

- Power-frequency voltage appearing in the tap-changer during test or in service.
- Impulse voltage appearing on the tap-changer during test on the transformer or in service.

Highest phase service voltage across the regulating winding

Example

115 kV ± 16 % regulating range Y connected gives the parameter in question as

$$\frac{115 \cdot 0.16}{\sqrt{3}} = 10.6 \text{ kV}$$

This value has to be compared with highest permissible phase service voltage across the regulating winding detailed in the applicable technical guide. This parameter may in some rare cases be a limiting factor.

RATED THROUGH CURRENT

The rated through current of the tap-changer should be not less than that resulting from the highest value of tapping current of the tapped winding of the transformer.

OCCASIONAL OVERLOADING

The ABB tap-changers have been designed to continuously carry a current of 1.2 times the maximum rated through current. In line with IEC 60214.

SHORT-CIRCUIT CURRENT STRENGTH

The tap-changer short-circuit current is given in the applicable technical guide.

PHASE STEP VOLTAGE

If the step voltage varies over the range, full details together with associated currents are needed to calculate the maximum breaking capacity. Limit values are given in the applicable technical guide.

TAPPING RANGE AND TAPPING ARRANGEMENT

The number of tapping positions has to be considered when selecting type of tap-changer, as the different types have different maximal tapping range.

- UZ 33 positions
- UB 27 positions
- UC 35 positions

Tapping arrangement (i.e. linear, reversing or coarse/fine) may also restrict type of tap-changers.

RECOVERY VOLTAGE

If the service voltage and the winding capacitance exceed certain limit values stated in the technical guide, tie-in resistors have to be used in order to avoid difficulties with regard to dielectric stresses within the change-over selector in the tap-changer.

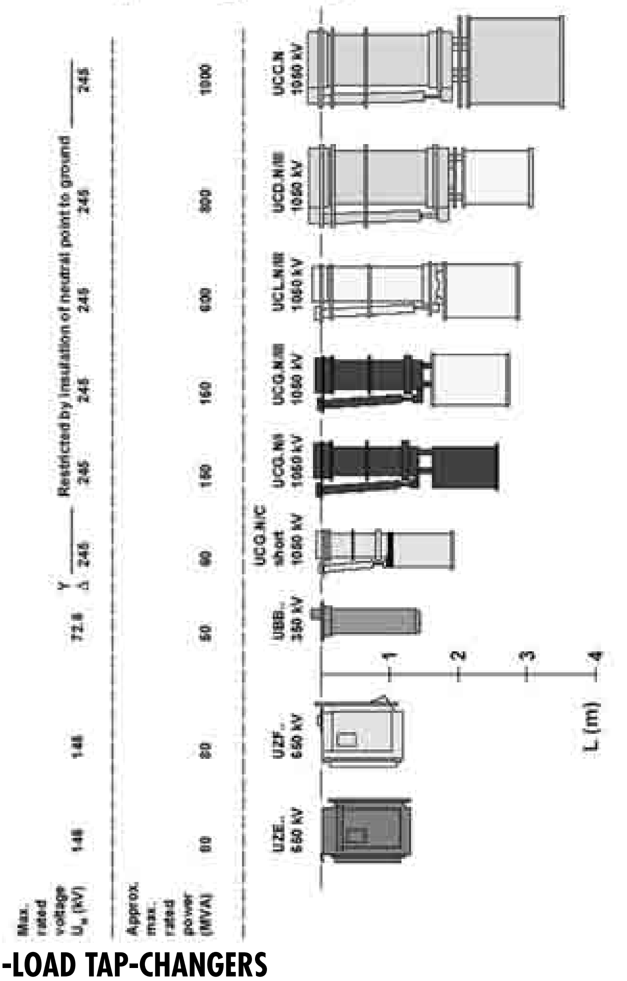
CONTACT LIFE

The predicted contact life is a function of the rated through current and has to be compared with the requirements.

TEMPERATURE CONDITIONS

The temperature of the oil or ambient air temperature surrounding the tap-changer can be in the range between –25 °C and +105 °C during normal service without any special precautions. The range can be extended to –40 °C provided the oil viscosity is between 200 to 800 mm2/s (cst).

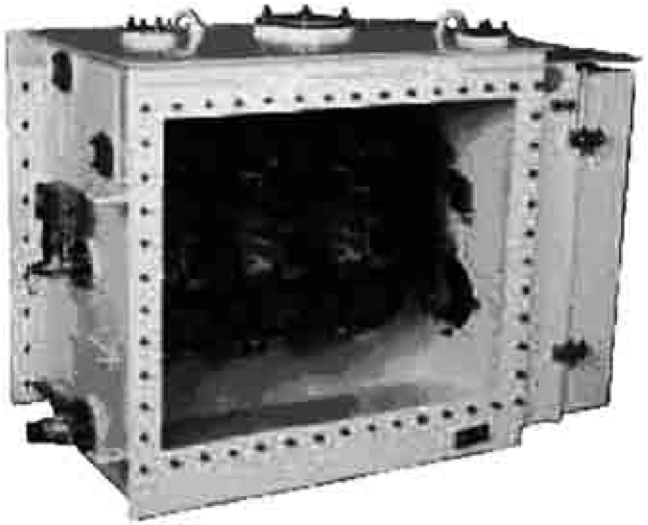
On-load tap-changer range



ON-LOAD TAP-CHANGERS

The UZ types of on-load tap-changers are of the single compartment on-tank type. The selector and switching mechanisms are combined (selector switch) and are located in the main compartment, with the motor-drive mechanism welded to the outside. The unit is supplied ready to mount on the outside of the transformer tank.

The UBB type of on-load tap-changer is designed for mounting inside of the transformer tank, but contains features usually found with the on-tank type of tap-changer.



This combination of the best qualities from both designs of tap-changer makes the UBB model unique in its design and operation.

Primarily designed for the medium sized transformer, the unit is compact and less costly than the equivalent diverter switch type of tap-changer.

The UC types of tap-changers are designed for mounting inside the transformer tank suspended from the transformer cover.

The tap-changer consists of two main components, the diverter switch and the tap selector. Both are driven, via shafts and bevel gears, by a motor-drive mechanism. The diverter switch is immersed in oil in its own housing to prevent contamination of the oil in the transformer tank. The switch is spring operated.

The breaking contacts are made of copper/tungsten. The current carrying contacts are made of copper or silver/copper, promoting good conductivity and low temperature rise.

The tap selector consists of fixed contacts located on an insulating structure. The structure forms a cage around the two central shafts which carry the moving contacts. A Geneva gear, located at the top of the selector, operates the shafts alternately.

MOTOR-DRIVE MECHANISMS

The motor-drive mechanisms used together with tap-changers type UB and UC are normally mounted on the side of the transformer tank and connected by a drive shaft and bevel gear.

The motor drive cabinets contain all the necessary equipment for operating the tap-changer. Special equipment can be supplied in order to fulfill customer requests. Degree of protection is IP 56 according to IEC 60529.

The motor drive type BUE is available in two versions

- BUE 1: Standard version
- BUE 2: Extra space for accessories

The cabinet is welded sheet steel and is treated for outdoor usage. The BUE 1 and BUE 2 can be used together with all tap-changers type UB and UC.

The motor drive type BUL is the optimal choice for all single-compartment in-tank

tap-changers, except for UCC and UCD, and when only a limited number of accessories is needed.

The cabinet is welded sheet steel and is in standard version hot dip galvanised.

DRY TYPE TRANSFORMERS FOR NON-LINEAR LOADS

Schneider Electric

NON-LINEAR LOADS AND HOT NEUTRALS

Many types of common office equipment, such as computers, copiers, printers, FAX machines and video display terminals are designed with switched-mode power supplies. As the volume of such equipment grows to become a major portion of an office's electrical load, the peculiar current demand characteristics of switched-mode power supplies have created some unusual problems:

- Circuit breakers trip or fuses blow at currents far below their rating.
- Neutral cables and panelboard neutrals are much hotter than their ratings, even with a balanced load.
- Distribution and lighting transformers supplying these loads overheat, even when amperage measurements show the load current is within its rating.

The root cause for these problems lies with the non-linear nature of switched-mode power supplies.

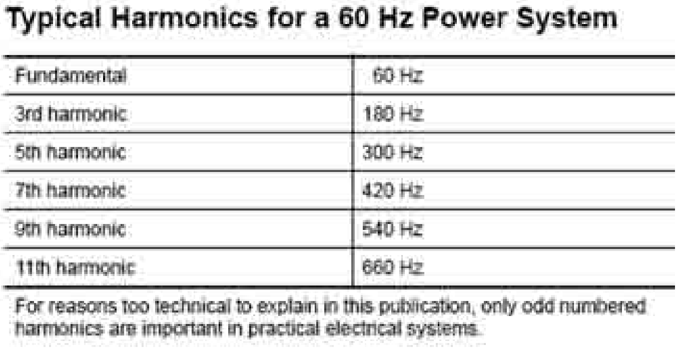
They draw current only in brief pulses at the top of each supply voltage half-cycle. When these loads are connected line-to-neutral on three-phase WYE voltage supplies, the current pulses only occur on one phase at a time. Therefore, each line current pulse must return in the supply neutral. The maximum neutral current occurs when all of the line-to-neutral loads are balanced on the three phases, and can be as high as 1.73 times the line current. Many installations require doubling either the size or the number of neutral cables, as well as increasing the size of panelboard neutrals and transformer neutral terminals to accommodate these additional conductors.

HARMONICS: A MEASURE OF NON-LINEARITY

Distorted current waveforms cannot be measured accurately with standard ammeters. Most standard meters are accurate only when measuring sinusoidal current. Harmonic current distortion can become severe enough to cause standard meters to indicate either more or less current than the actual, effective current flowing. The ratio between actual and measured current can be as high as 2:1. In many instances, special "true RMS" meters are required for accurate current measurement.

Through mathematical analysis, even the most distorted waveform can be broken down into multiple higher-frequency sinusoidal components which, when added together, will produce the original waveform. These frequencies are called harmonics.

Thus, non-linear current waveforms are said to contain "harmonic distortion". Distorted current waveforms can be described as a "recipe" of various proportions of harmonic numbers. The 3rd harmonic of a 60 Hz supply would have a frequency of 180 Hz (3 X 60 = 180).



Typical Harmonics for a 60 Hz Power System

Fundamental	60 Hz
3rd harmonic	180 Hz
5th harmonic	300 Hz
7th harmonic	420 Hz
9th harmonic	540 Hz
11th harmonic	660 Hz

For reasons too technical to explain in this publication, only odd numbered harmonics are important in practical electrical systems.

The major components in the harmonic current spectrum of switched-mode power supplies are the third and fifth harmonics.

HARMONICS AND TRANSFORMERS

Transformer coil conductors operate in strong magnetic fields and are close to large masses of metal, such as the transformer core and structural supports and enclosure parts. Such conditions cause extra heating in coil conductors called "stray losses". Transformers are designed to operate at safe temperatures with these stray losses taken into account. When a transformer is supplying non-linear loads, however, stray losses increase dramatically at currents containing higher frequencies than 60 Hz.

The increased stray losses can cause the coils to reach elevated temperatures far beyond their design rating. Thus ,transformers expected to supply non-linear loads must be oversized by a factor depending on the severity of the harmonics and the amount of stray losses in the transformer.

Stray losses vary greatly with transformer size and from one manufacturer to another in any given size.

This is particularly true in the 15 kVA to 500 kVA range, the vast majority of distribution and lighting transformers. Therefore, rule-of-thumb derating (over-sizing) might be adequate for one size or manufacturer and not another.

TEMPERATURE RISE AND K-FACTOR

The difference between average temperature rise and hot spot temperature in a transformer varies depending on the severity of the current distortion present in the load. In addition, the primary and secondary windings of a transformer can differ significantly in their sensitivity to the heating effects of higher frequency current components. The NL and NLP transformers are designed for a maximum hot spot temperature of 220°C at their rated K-factors. Although the actual average temperature rise of these transformers will be less than 115°C under rated non-sinusoidal load, there are no inherent continuous overload capacities normally expected at that temperature rise if used at their maximum K-factor rating. Because of this variable relationship between temperature rise and maximum hot spot temperature, and because the industry has not yet precisely defined the hot spot vs. average temperature rise relationship in transformers carrying severe non-linear loads, it is suggested that job specifications only use 115°C or 80°C rise to prevent the possibility of hot spot temperatures exceeding the 220°C insulation rating.

THE ELUSIVE K-FACTOR

Non-linear loads such as computers do not have a constant current distortion characteristic associated with them. The current distortion in the lines to these devices varies with the amount of distortion in the voltage supplied to them. In turn, the voltage distortion depends on the source impedance and the amount of total load on the system. Computers plugged into very large capacity, or "stiff", systems will exhibit very high harmonic distortion in their current signature. Conversely, smaller, or "soft", systems will create greater voltage distortion as a result of the non-linear current, and cause less current distortion. Also, the current distortion in any system will vary significantly with the number of non-linear loads connected.

The dependence of current distortion on the load amount and system impedance means that a K-factor number cannot be assigned to specific pieces of equipment. The impedance of transformers tends to limit the amount of K-factor that they will supply to a load. That limitation is slight at light loading, producing comparatively large K-factor numbers on the load current. However, the full load current distortion determines the K-factor required on the transformer. At full load, the voltage distortion on the transformer is greatest, reducing the current distortion significantly. Normal impedance transformers (3–5%) will typically limit 100% non-linear commercial office loads to K-7 or less. Abnormally low impedance transformers (<3%) will cause higher current distortion, higher neutral current, and increased transfer of harmonics into the upstream, primary system.

Because it is rarely possible to measure transformer harmonics when fully loaded, the K-factor choice is based typically on transformer manufacturer guidelines.

THE NL SOLUTION

Three special considerations exist for the design of transformers intended to be used on non-linear loads:

1. Winding conductors must be either oversized to compensate for increased stray losses, or strays must be reduced in the coil design.

2. The core must be designed at a reduced induction level to allow a safety margin for increased core loss caused by distorted input voltage.

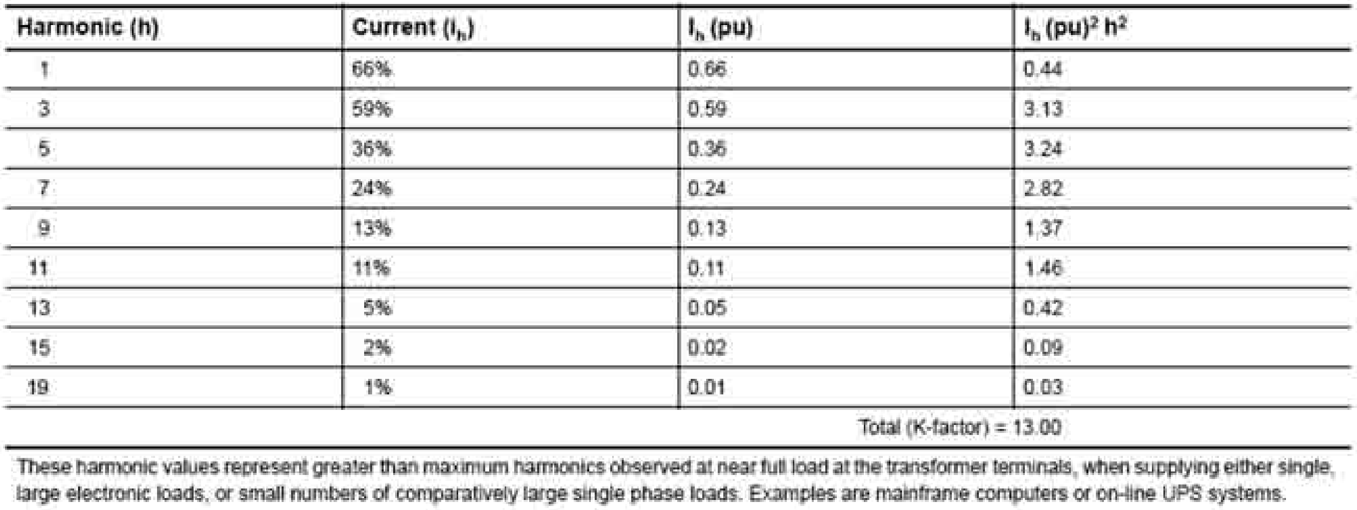
3. The transformer neutral terminal must be increased in both ampacity and lug pad area to accommodate more neutral conductors.

The type NL transformer requires no derating for non-linear loads with a total Ih(pu)2h2 (K-factor) of 4.0. The following load analysis is an example of a K-4 load:

Harmonic (h)	Current (i_h)	I_h (pu)	I_h (pu)^2 h^2
1	76%	0.76	0.57
3	46%	0.46	1.90
5	17%	0.17	0.72
7	8%	0.08	0.31
9	5%	0.05	0.20
11	3%	0.03	0.11
13	2%	0.02	0.07
15	1%	0.01	0.03
19	1%	0.01	0.03
			Total (K-factor) = 4.00

These harmonic values are typical at near full load at the transformer terminals, when supplying office loads comprised of large numbers of 100% non-linear single phase electronic equipment.

The type NLP premium series transformer is designed for more severe applications and can operate at full rating with a total Ih(pu)2h2 (K-factor) load value of 13.0. The following load harmonics are an example of a K-13 requirement:



Harmonic (h)	Current (I_h)	I_h (pu)	I_h (pu)^2 h^2
1	66%	0.66	0.44
3	59%	0.59	3.13
5	36%	0.36	3.24
7	24%	0.24	2.82
9	13%	0.13	1.37
11	11%	0.11	1.46
13	5%	0.05	0.42
15	2%	0.02	0.09
19	1%	0.01	0.03
			Total (K-factor) = 13.00

These harmonic values represent greater than maximum harmonics observed at near full load at the transformer terminals, when supplying either single, large electronic loads, or small numbers of comparatively large single phase loads. Examples are mainframe computers or on-line UPS systems.

FREQUENTLY ASKED QUESTIONS

Q. What is K-factor and how can I use it to specify transformers?

A. K-factor is a simple numerical rating that can be used to specify transformers for non-linear loads. Harmonic analysis instruments can determine the full load per-unit value of true-RMS current for each harmonic; called Ih(pu). The products of the square of this value and the square of the harmonic numbers (h) can be summed for the fundamental and all harmonics to obtain the K-factor number for that load current.

Q. How can I determine the harmonic content of my load?

A. It is very difficult to estimate the severity of load harmonics using general guidelines. The main reason is that a given load will produce a varying amount of current distortion depending on the source system impedance and the amount of load on that system. Many consulting services have instrumentation to analyze power systems. Harmonic analysis can be used to calculate the K-factor rating. You must remember, however, that K-factor changes with load and only full load analysis is relevant to the choice of transformer K rating.

Q. How can I predict harmonic levels and potential problems in new construction?

A. Consultants are rapidly developing data based on installation experience. Given a good picture of the quantity and mix of equipment loads, a safe guideline envelope can be specified based on previous data. IEEE guide standards like IEEE-519 are valuable tools for estimating what to expect in both commercial and industrial installations.

Q. If I'm unsure of loads, or future changes are likely, how can I choose between the NL or the NLP transformer design?

A. The full load current distortion on normal impedance transformers (3–5%) supplying commercial office loads will translate to a maximum K-factor of 7. The K-13 rating of the type NLP product is always a conservative choice. However, the K-4 rated type NL will be quite adequate for average installations. At worst, the type NL transformer would only be derated by 5% maximum if it were presented with a K-7 load.

Q. I've been using "rule-of-thumb" oversizing of standard transformers for some time in this application. Why should I buy special designs?

A. Commercial office load harmonics typically require derating standard general purpose transformers to approximately 80% of their nameplate rating at worst. However, the practice of intentionally oversizing transformers to compensate can result in increased installation costs because the higher kVA nameplate can require larger circuit breakers and wiring to comply with NEC. Standard general purpose transformers are normally supplied with 100%-rated neutral terminals. The increased neutral current characteristic of line-to-neutral non-linear loads could exceed the neutral terminal rating on such transformers.

Q. What is the purpose of the electrostatic shield in NL and NLP transformers?

A. Electrostatic shields do not perform any function with regard to harmonic current or voltage distortion issues. However, shields may be extremely valuable in protecting sensitive equipment from some types of common-mode electrical noise and transients generated on the line side of the transformer.

Q. Can I obtain special designs in the NL or NLP series, such as special voltages, lower temperature rise, copper windings, low sound levels, or other special features?

A. Many modifications of the NL and NLP series transformers are available.

Q. Can harmonic currents in my system be reduced or eliminated?

A. The switched-mode power supplies in electronic equipment that cause non-linear current need this current to operate efficiently. Any devices designed to reduce the flow of harmonic current to these power supplies can possibly cause equipment malfunction. However, there are several techniques to reduce the level of current distortion carried back into the supply system.

Q. Can the NL or NLP transformers be used for motor drives?

A. Although motor drives also represent non-linear loads, the current distortion for standard AC and DC drives contain mainly 5th and 7th harmonics. This is quite different from the 3rd and 5th harmonic current characteristics produced by switched-mode power supplies connected line-to-neutral, found in commercial office loads. Type NL and NLP transformers are specifically designed and optimized for office electronic loads and are not recommended for drive load applications.

ABOUT CLOR-N-OIL FIELD TEST PROGRAM

Vasu H. Tahiliani, EPRI, Palo Alto, California

Note: This report presents the summary of test results from 40 utilities.

A total of 879 oil samples have been tested both with the CLOR-N-OIL test kit as well as on a gas chromatograph. Whenever a CLOR-N-OIL kit user recognized that he erred on his test procedure, either through breaking the capsules in the wrong order or spilling some fluid, the test results were discarded for this summary report.

Of the 879 samples, 424 tested negative (with a blue color at the end of the test) indicating less than 50 ppm of PCB. The remaining 455 tested positive (turned clear). However, not all of these samples were drawn randomly, since many users wanted to explore this test method in a narrow critical range of PCB contamination. This led to a larger percentage of oil samples testing clear.

If we were to choose only randomly picked samples, the test results show 372 (51%) blue and 352 (49%) clear. Of the 355 clear samples 161 (22% of the total) did contain more than 50 ppm of PCB and 194 samples (27% of the total) gave a false positive test. This, in comparison to 51% of the samples being eliminated from any further tests, is quite small. Of course, one would like this percentage to get even smaller, but in order to safeguard against contaminated samples testing negative, this is the best we can do.

A total of 18 tests showed false negatives, i.e., the CLOR-N-OIL test gave a negative (blue) test, but a subsequent PCB test indicated a contamination level greater than 50 ppm. While we continue to examine the reasons and retest many of these samples, we do have an explanation for many of the tests.

A user who reported four false negative readings in a batch of 20 tests subsequently found that the PCB tests carried out by an independent outside lab gave high PCB readings. The PCB test reported by the lab gave readings between 53 and 26 ppm, whereas the subsequent tests carried out on these same samples at General Electric tested between 2 and 11 ppm.

There were two other problems early in the test program that were rectified through appropriate changes in the instructions. One change was to show through a photograph that if a test sample has a substantial per-centage of PCB (above a few hundred thousand ppm), the test sample being heavier than water will sink below the water and this test method will not work.

Another problem was eliminated through the removal of a photo showing a test resulting from a sample contaminated with 40 ppm of Askarel 1242. Here the photograph showed a slight purple ring at the top of the water layer which would look similar to a test sample if some oil was transferred to tube #2 (in step 4 of the instructions). Since the instructions were revised only two false negatives have been reported.

CONCLUSIONS:

Through the use of the CLOR-N-OIL screening test one can typically eliminate half of the oil samples from any further testing. The general experience, especially since the instructions were revised, has been exceptionally good. This test method can offer a significant cost savings to the utility industry.

Number of Utilities Participating	87
Number of Utilities that have Reported to Date	40
Total Oil Samples Tested	879
Blue	424 (48%)
Clear	455 (52%)
Random Sampling	
Blue	372 (51%)
Clear	355 (49%)
False Positives	194 (27%)
PCB Contaminated	161 (22%)
False Negatives	18 (2.3%)

TRANSFORMER MAINTENANCE INTERVAL MANAGEMENT

Roy Moxley and Armando Guzmán

Schweitzer Engineering Laboratories, Inc. Pullman, WA

ABSTRACT

Recent surveys indicate that the average age of utility power transformers exceeds 30 years. Managing these critical assets requires monitoring the factors that cause transformer damage. Excessive heat and mechanical stress during through faults on transformers are recognized as the two major causes of damage. New technology in transformer protection relays provides for both thermal and through-fault monitoring. This paper demonstrates how to use the transformer thermal damage and loss-of-life information from IEEE Std. C57.91-1995 to schedule proactive maintenance. It also presents through-fault recording and accumulated data and discusses how these relate to transformer short-circuit standards.

INTRODUCTION

In the historical struggle between AC and DC power transmission, AC is generally preferred because it allows easy conversion of voltages to higher levels for long distance transport. Power transformers are a critical link in the AC path of electricity from the generating stations to end users. In terms of total investment, electric utilities invest at least as much in transformers as they do in generating stations. In many cases, because of the larger installed base, utilities invest more in transformers. Transformers are expected to last from 20–30 years and, in many cases, even longer. Because regulators and financial markets measure a utility's ability to make efficient use of resources, utilities must maximize asset utilization. Based on transformer design and experience, we know that the amount of service a transformer "sees" is an indicator of serviceability. As they say, "it's not the age—it's the mileage". Measurable indicators of transformer serviceability include electrical load; top-oil, hottest-spot, and ambient temperatures; fault history; and dissolved gas analysis. Utilities that use these indicators can make intelligent profit/risk decisions and plan optimal transformer loading and maintenance.

MEASUREMENTS

The best way to protect and extend the life of transformers is to collect information such as load and fault current as well as top-oil or hottest-spot temperatures, and receive notification when a value has reached a preset level. Logically combining these quantities can help predict or anticipate an alarm condition, and keeping a record of these measurements provides a more complete picture of the transformer's insulation condition. The challenge is providing a means to collect this information without creating a massive new system requiring its own maintenance and cost structure. Protective relays that are permanently connected to the transformer current (and possibly temperature inputs) as shown in Figure 1, have memory and recording capability, and have logical decision making capacity, can be the beginning of a comprehensive "life management" system for transformers.

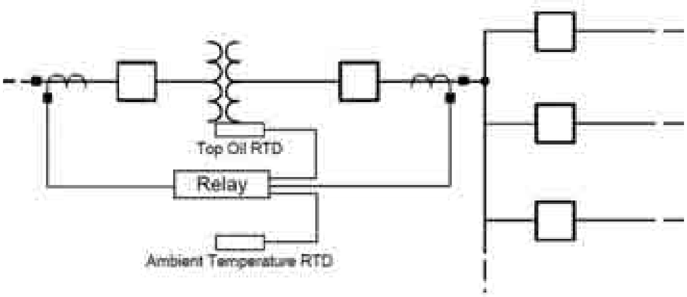


Figure 1 Transformer Relay With Connected RTDs for Thermal Monitoring

Construction and usage standards for transformers provide a starting point for applying these measurements to determine optimal loading at a given ambient temperature and predict when it is appropriate to schedule maintenance prior to a life-ending event.

TEMPERATURE MEASUREMENTS AND CALCULATIONS

IEEE standards and numerous technical papers have established guidelines for loading transformers based on temperature limits for oil and conductors. For example, recognizing that a "loss of life" occurs as temperatures increase, *IEEE Standard C57.115-1991: Guide for Loading Mineral-Oil-Immersed Power Transformers Rated in Excess of 100 MVA (65ºC Winding Rise)*, Table 2, includes temperature limits for different load conditions. All of the conditions above normal loading involve some degree of an accelerated loss of life of the transformer [1] [2].

The standard shows that from a managed ownership standpoint, regularly overloading a transformer at high ambient temperatures causes accelerated aging. The question is: how should maintenance of the transformer change based on the amount and duration of overloads?

Both operator actions and system events can cause transformer overloads. Therefore, temperatures should be continuously monitored, and accumulated loss of life should be measured and recorded. The most important two values to calculate or measure are hottest-spot temperature and top-oil temperature. IEEE Std. C57.91-1995 provides formulas for performing these calculations. We have programmed these formulas in protective relays to calculate temperatures. The user inputs the transformer constants required (see Appendix A), such as thermal time constants, ratio of no-load to load losses, and total losses at rated output. If these constants are unknown, the standards provide reasonable default values for approximate calculations.

Using the entered constants, the relay provides instantaneous and accumulated loss-of-life and aging acceleration factor alarm points. Calculations are based on what information is available. Temperature devices on the transformers, such as Resistance Temperature Detectors (RTDs), may or may not be available, so different calculations are made depending on this availability [3].

THERMAL CALCULATIONS USING AMBIENT AND TOP-OIL TEMPERATURES

In this case, the relay receives measured ambient and top-oil Transformer Relay With Connected RTDs for Thermal Monitoring Construction and usage standards for transformers provide a starting point for applying these measurements to determine optimal loading at a given ambient temperature and predict when it is appropriate to schedule maintenance prior to a life-ending event.

THERMAL CALCULATIONS USING AMBIENT AND TOP-OIL TEMPERATURES

In this case, the relay receives measured ambient and top-oil and uses the top-oil temperature to calculate the hottest-spot temperature.

A single-tank, three-phase transformer can have as many as two thermal inputs: the ambient temperature input and the top-oil temperature input. Independent, single-phase transformers normally have as many as four thermal inputs: an ambient temperature input and a top-oil temperature input for each one of the three tanks. During a fixed time interval, Δt = 1 minute, the relay calculates the winding hottest-spot temperature at the end of the interval, according to the following expression:

$$\Theta_H = \Theta_{TO} + \Delta\Theta_H$$

where:

Θ_H = winding hottest-spot temperature, °C

Θ_{TO} = top-oil temperature, °C

$\Delta\Theta_H$ = winding hottest-spot rise over top-oil temperature, °C

The relay calculates winding hottest-spot rise over top-oil temperature, Δ_H, according to the following:

$$\Delta\Theta_H = (\Delta\Theta_{H,U} - \Delta\Theta_{H,i}) \cdot \left(1 - e^{\frac{-\Delta t}{60 \cdot \tau_W}}\right) + \Delta\Theta_{H,i}$$

where:

$\Delta\Theta_{H,U}$ = the ultimate hottest-spot rise over top-oil temperature for any load, °C

$\Delta\Theta_{H,i}$ = initial hottest-spot rise over top-oil temperature at the start time of the interval, °C

τ_W = winding time constant of hot spot, in hours

Δt = one-minute temperature data acquisition interval

$\Delta\Theta_{H,U} = \Delta\Theta_{H,R} K^{2m}$

where:

K = load expressed in per unit of transformer nameplate rating according to the cooling system in service (phase current divided by the nominal current)

m = winding exponent

$\Delta\Theta_{H,R}$ = rated winding hottest-spot rise over top-oil at rated load, °C

The implementation of this equation over time is shown in Figure 2 below.

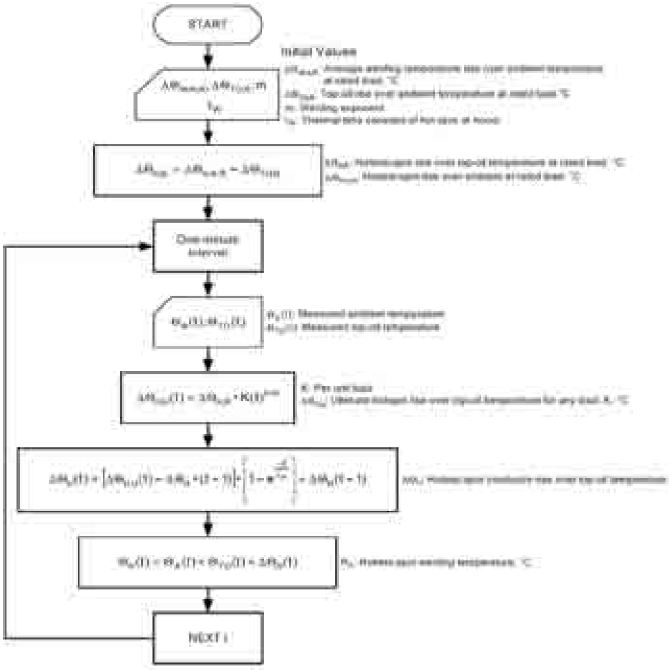


Figure 2 Iterative Real-Time Hottest-Spot Calculation

THERMAL CALCULATIONS WITH ONLY AMBIENT TEMPERATURE INPUTS

If only ambient temperature is available, the relay calculates both top-oil temperature and hottest-spot temperature. Typical variances in ambient temperature for the same load could result in a difference in aging of transformer insulation by 100 times, so it is critical that ambient temperature is available.

Where the relay has a measured ambient temperature input without a top-oil temperature input, you have one thermal input (for ambient temperature) regardless of whether you have a single three-phase transformer or independent single-phase transformers. The relay calculates winding hottest-spot temperature, _H, according to the equation in the earlier case:

$$\Theta_H = \Theta_{TO} + \Delta\Theta_H$$

and calculates top-oil temperature, _TO, according to the following:

$$\Theta_{TO} = \Theta_A + \Delta\Theta_{TO}$$

where:

Θ_A = ambient temperature, °C

$\Delta\Theta_{TO}$ = top-oil rise over ambient temperature, °C

The relay calculates top-oil rise over ambient temperature according to the following:

$$\Delta\Theta_{TO} = (\Delta\Theta_{TO,U} - \Delta\Theta_{TO,i}) \cdot \left(1 - e^{\frac{-\Delta t}{60 \cdot \tau_{TO}}}\right) + \Delta\Theta_{TO,i}$$

where:

$\Delta\Theta_{TO,U}$ = the ultimate top-oil rise over ambient temperature for any load, °C, and is a function of load

$\Delta\Theta_{TO,i}$ = initial top-oil rise over ambient temperature at the start time of the interval, °C

τ_{TO} = top-oil time constant of transformer, in hours

The relay calculate the ultimate top-oil rise over ambient temperature, Δ_TO,U, according to the following expression:

$$\Delta\Theta_{TO,U} = \left(\frac{K^2 \cdot R + 1}{R + 1}\right)^n \cdot \Delta\Theta_{TO,R}$$

where:

R = ratio of load loss at rated load to no-load loss

n = oil exponent

$\Delta\Theta_{TO,R}$ = top-oil rise over ambient temperature at rated load, °C

For any n (oil exponent) value and any load value, the relay calculates the thermal top-oil time constant according to the following expression:

$$\tau_{TO} = \tau_{TO,R} \cdot \left(\frac{\frac{\Delta\Theta_{TO,U}}{\Delta\Theta_{TO,R}} - \frac{\Delta\Theta_{TO,i}}{\Delta\Theta_{TO,R}}}{\left(\frac{\Delta\Theta_{TO,U}}{\Delta\Theta_{TO,R}}\right)^{\frac{1}{n}} - \left(\frac{\Delta\Theta_{TO,i}}{\Delta\Theta_{TO,R}}\right)^{\frac{1}{n}}} \right)$$

where

$\tau_{TO,R}$ = thermal time constant in hours at rated load with initial top-oil temperature equal to ambient temperature

Real-time values include calculated temperatures as well as loss-of-life accumulations. Instantaneous values are useful to operators in making dispatch decisions.

Transformer standards provide guidelines for operating at "damaging" thermal levels. For example, Table 1 from IEEE Std. C57.115-1991 provides what can be considered reasonable loading times for given hottest-spot temperatures [1]. Operators or relays should act to limit the time at higher-than-rated temperatures. Relay contacts or alarms sent via SCADA can also initiate control actions to reduce load.

INSULATION AGING

Hottest-spot temperature above 90–105ºC causes irreversible degradation of the cellulose insulation structure of a transformer [4] [5]. This degradation accumulates over time until the insulation material fails. The mode of the insulation failure in these cases is typically of a mechanical nature, e.g., cracking and flaking caused by the heavy carbonization of the insulation material. This mechanical degradation of the insulation material eventually results in an electrical failure of the device.

INSULATION AGING ACCELERATION FACTOR

Based on transformer standards, we calculate an insulation aging acceleration factor, FAA, which indicates how fast the transformer insulation is aging.

We calculate the insulation aging acceleration factor, FAA, for each time interval, Δt, as follows:

LOSS OF LIFE

Now we calculate daily rate of loss of life (RLOL, percent loss of life per day) for a 24-hour period as follows:

$$RLOL = \frac{F_{EQA} \cdot 24}{ILIFE} \cdot 100$$

where:

RLOL = rate of loss of life in percent per day

ILIFE = expected normal insulation life in hours

To provide the user with trend information on the loss of insulation, the RLOL value should be automatically recorded. The equivalent life at the reference hottest-spot temperature (95ºC or 110ºC) that will be consumed in a given time period for a given temperature cycle is:

$$F_{EQA} = \frac{\sum_{n=1}^{N} F_{AA_n} \cdot \Delta t_n}{\sum_{n=1}^{N} \Delta t_n}$$

where:

F_{EQA} = equivalent insulation aging factor for a total time period

n = index of the time interval, Δt

N = total number of time intervals for the time period

F_{AA_n} = insulation aging acceleration factor for the time interval, Δt_n

Δt = time interval

During 24 hours, the total number of time intervals is:

$$N = \frac{24}{\left(\frac{\Delta t}{60}\right)} = \frac{1440}{\Delta t}$$

where:

Δt = time interval

Because the time intervals and the total time period used in the thermal model will be constant, we can simplify the calculation of FEQA to the following:

$$F_{EQA} = \frac{\sum_{n=1}^{N} F_{AA_n}}{N} \qquad \text{(equivalent life in days)}$$

where:

$TLOL_d$ = total accumulated loss of life, TLOL

$RLOL_d$ = most recent daily calculation

$TLOL_{d-1}$ = previous TLOL

An estimate of the total accumulated loss-of-insulation life in percentage of normal insulation life can be made by summing all of the daily RLOL values: TLOL

Damage, or aging of insulation, roughly doubles with every 6–8ºC of temperature above 90ºC [5]. We can plot the approximate effects of hottest-spot temperature on insulation aging as shown in Figure 3.

Accumulated loss of life provides an indicator of the impact of operational overloads on the transformer. Simply, it is the integral over time of the accumulated aging, taking into account the effect of accelerated aging caused by elevated temperatures.

Moisture content in the cellulose insulation has a significant impact on insulation aging [4] [6]. If the moisture content increases from 0.5% to 1.0%, the rate of aging of the cellulose insulation at least doubles for a given temperature. Moisture in the insulation can be estimated by applying an appropriate algorithm [7] to the measured water content in the oil. Because it is important to know the amount of water in the transformer oil, even an advanced temperature monitoring system cannot completely predict the perfect time to perform maintenance. Using the calculated moisture content to adjust the thermal aging of the insulation improves the ability to predict maintenance.

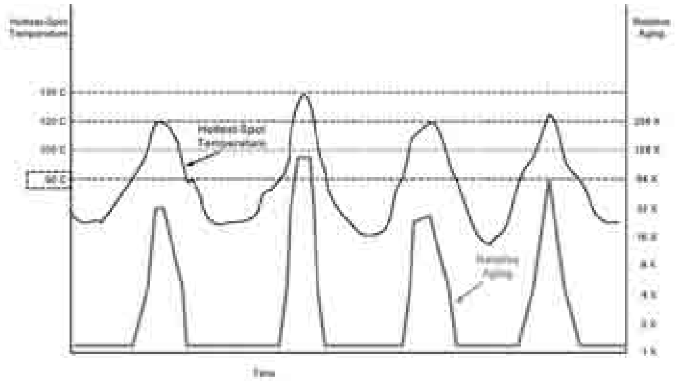


Figure 3 Relative Aging vs. Hottest-Spot Temperature

COMPARING CALCULATED AND MEASURED VALUES

While it is advantageous to have top-oil and hottest-spot temperatures available from direct measurements, calculated values are also useful. Obviously, for a transformer without top-oil or hottest-spot RTDs, a calculated value is the only one possible. The calculated values for top-oil and hottest-spot temperatures can be derived using load currents and either measured or fixed (manually entered setpoint) values for ambient temperature. When based on assumed ambient temperatures, the calculated values will be very unreliable.

If measured oil temperatures are available, then it is possible to compare the calculated values with the measured values. This gives an indication of the effectiveness of the cooling system. An alarm can be issued if the difference between measured and calculated temperatures exceeds a preset value. Failed pumps, birds' nests in the fans, or any number of other problems can be detected and corrected this way, before they cause a catastrophic transformer failure. Comparing calculated and measured values can also be used to correct setting constants.

THROUGH-FAULT MONITORING AND ALARMS

According to insurance industry studies [8], through faults are the number one cause of transformer failure today. Initiation of a through fault can be seen in Figure 4 below.

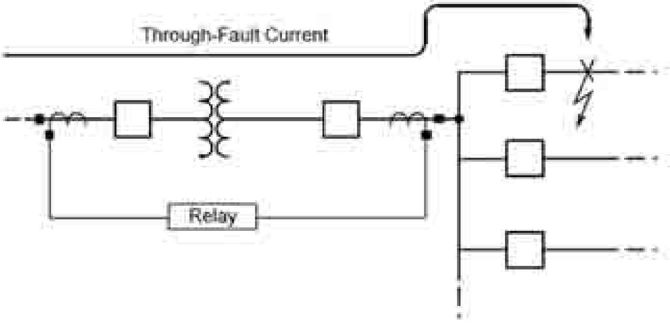


Figure 4 One-Line Diagram of a Typical Through-Fault Event

As fault duty and feeder exposure increase, the incidence and severity of through faults experienced by a transformer will tend to go up over time. IEEE Std. C57.12 [9] provides construction guidelines for short-circuit withstand for transformers. The standard states that a transformer shall withstand 2 seconds of a bolted fault at the transformer terminals. Testing to verify through-fault withstand capability is normally performed on a design basis, with the length of the test limited to 0.5 seconds for up to 30 MVA three-phase transformers.

When evaluating how to assess possible damage or loss of life to an installed transformer subjected to a through fault, it is interesting to consider testing standards and their implications. The test standards are "intended for use as a basis for performance [10]". Test standards are established only for new units, to some degree in recognition that normal service life of a transformer will cause it to have an unpredictable response to short-circuit tests; yet those tests are a simulation of what the transformer may experience with the next through fault.

Following short-circuit tests, a careful set of visual and electrical tests is performed to verify there has been no, or minimal, movement of the coils as a result of the forces incident to a short circuit. In an installed transformer, it is generally not practical to perform even minimal visual and electrical tests following every through fault. So the question is: what is a reasonable expectation of length of life of a transformer, built to accepted standards, following normal through faults that every system will experience?

Plotting a comparison of the stresses a transformer experiences and its withstand capability against time could produce a graph such as Figure 5 [6].

The stress withstand capability of a transformer is reduced gradually by degradation caused by overheating of the insulation components. The stresses the transformer is subjected to may increase over time due to increasing loads and an increase in short-circuit duty from additional system interconnections and sources. If we were to modify Figure 5 to include

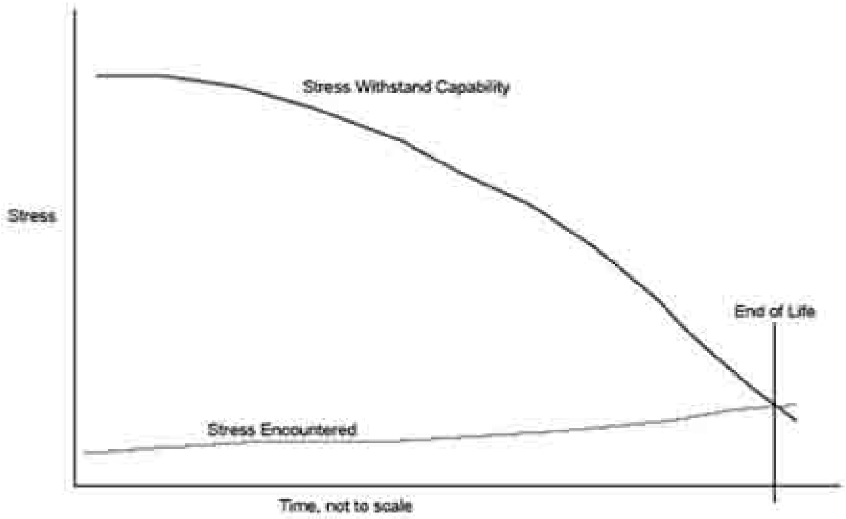


Figure 5 Stress Withstand Capability Over Transformer's Lifetime

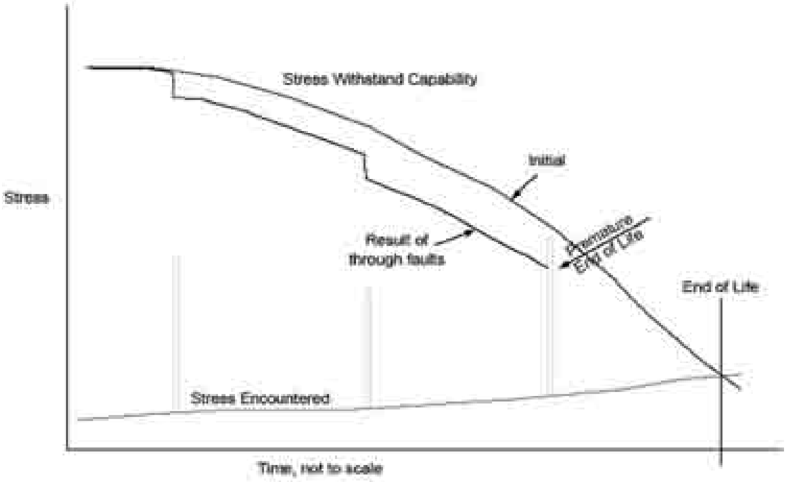


Figure 6 Stress Withstand Capability Over Transformer's Reduced Lifetime

more detail, also shown by Reference [6], we could create a graph such as Figure 6.

In this case, the transformer experiences three severe through faults. The first two faults reduce the transformer's withstand capability to the point where it cannot withstand the forces of the third fault. While not explicitly stated in IEEE standards (see [9]) this degradation in capability is predicted by the following equation [11]:

$$I^2 t = k \qquad (1)$$

Where:

k generally equals a constant where t equals 2 seconds and I equals maximum fault current in per unit times normal base current. This matches the construction characteristics defined in IEEE Std. C57.12.

For example, for a transformer rated 40 MVA base rating, 230/69 kV and a 4% impedance connected to an infinite bus, we would have:

$$\text{Base load current} = \frac{40}{\sqrt{3} \cdot 69} = 0.335 \text{ kA}$$

Equation 1 with maximum fault current then becomes

$$\left(\frac{40}{\sqrt{3} \cdot 69 \cdot 0.04}\right)^2 \cdot 2 \text{ sec} = 140 \text{ kA}^2 \text{ sec}$$

While this curve as presented in the IEEE standards [9] [11] is used for setting and coordinating protective devices for transformers, it can have practical applications to ongoing transformer service. In IEEE Std. C57.12, the transformer is constructed to be able to withstand this fault. This fault is the limit of what the transformer was designed to withstand; the testing standard provides for a design test of the transformer, when new, at a short-circuit duration of 1/4 of this time. Following the short-circuit test, the transformer is untanked and inspected visually for winding displacement or other damage. Electrical tests are performed to ensure insulation integrity and verify that parameters such as excitation current and impedance have not changed. Users can measure and record the fault duty seen by a transformer on the same basis as the design tests performed in the factory. This gives the user a basis for evaluating the service life remaining in the transformer before inspection and testing are required.

COMBINED MEASUREMENTS

Temperature loss-of-life calculations are based on a gradual and continual aging process similar to that shown in Figure 5. While sudden and severe overloading at high ambient temperature could cause a temporary increase in the aging "slope", as long as the overload is not so severe as to burn up the transformer, the process is akin to sliding down a hill and not falling off a cliff.

On the other hand, a through fault is a sudden and severe event by its very nature. As shown in Figure 6, the mechanical forces incident to the through fault can cause an insulation structure that is already aged by years of loading to fail.

The problem is that overloading guidelines do not take into account the short-circuit stresses that a transformer may have or may yet experience. Likewise, short-circuit design and testing standards are made for new units that have not experienced any aging of the insulation structure. The advantage of having one device perform both the thermal recording and loss-of-life calculation, as well as the through-fault monitoring and accumulated fault duty recording, is that now these two factors can be combined for an effective maintenance indicator.

For example, if we define TLOLL = Total Loss-of-Life Limit and ISQT = Accumulated I2t of fault duty, we can write a logic equation to initiate alarm for a transformer similar to that in the through-fault monitoring example:

$$\text{Alarm} = (\text{TLOLL} > 70\%) \text{ AND } (\text{ISQT} > 98 \text{ kA}^2 \text{ seconds})$$

This alarm can be a sign that because the transformer has an accumulated thermal loss of life of 70% as well as an accumulated through-fault duty of 70% of its nominal withstand capability, it is time for at least a thorough inspection and possibly an overhaul to reblock or even rewind. A possibly greater application is to use the outputs from the monitoring associated with electrical quantities with other transformer information that may be available. These other monitoring devices or methods can include sudden pressure relays, thermal imaging, and dissolved gas analysis.

Sudden pressure relays have been reported to have occasional problems with misoperation on external faults. For this reason, they are sometimes used for alarm only and not tripping [12]. An alarm from a sudden pressure relay may have more consequence as a maintenance predictor if coupled with an accumulated loss of life due to overload. Within a digital relay, it is a simple matter to either logically or electrically combine the output of the sudden pressure relay with the accumulated loss-of-life alarm. This allows recognition of degradation in insulation, making small movements of the core and coil assembly more significant, and possibly, events worthy of initiating an inspection.

Thermal imaging can be used to compare calculated top-oil temperatures with measured values, as suggested in the thermal monitoring section above. Cooling effectiveness, or the lack thereof, can then be evaluated prior to damage.

Dissolved gas analysis is more suited to be an interim step between an accumulation of events and a complete inspection than as a frequent diagnostic action, except on the largest transformers.

TURNING DATA INTO INFORMATION

It is not enough that data on overall loss of life exist inside a relay. It must be transmitted to a person who can use the information to improve decision-making and better manage the transformer asset. The simplest way to send data is to assign an alarm contact to a certain loss-of-life level. The problem is that this takes away the additional intelligence that may be available, as discussed in previous sections. Using a communications processor to send a complete report to a responsible engineer is a way to send more useful information (Figure 7).

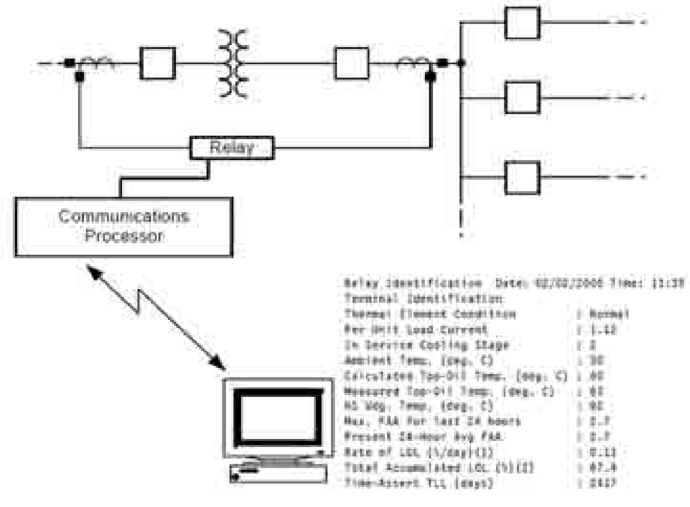


Figure 7 Using a Communications Processor to Send a Formatted Report

With more complete information, the engineer can assess the degree of risk associated with continuing with the transformer in service under the same conditions or performing maintenance. Combining multiple reports—such as thermal, through-fault, and online dissolved gas analysis— can give the best view of the conditions within the transformer.

CONCLUSIONS

While using the alarm point as a maintenance indicator may sound like additional work, doing so can actually prevent maintenance work. If a unit has not experienced an accumulated life duty to indicate that maintenance is necessary, then without some other indicator, maintenance is not necessary.

Transformers need to be utilized to their maximum capabilities, which mandate that maintenance actions and operating procedures take the consequences of maximum usage into account. Utilities that use all of the information available can postpone maintenance on units that have not seen excessive stress and accelerate maintenance schedules for units that have seen possibly damaging stress.

As transformer design tools improve, they not only provide for designs that are more assured of meeting standards, but they also allow transformer designers to avoid safety margins that may have existed in prior designs. This makes it more important to recognize what these design standards provide and how to measure when the limits defined by standards are approached.

1. A comprehensive transformer management plan continuously monitors and records thermal loading.
2. Comparing measured top-oil temperatures with calculated top-oil temperature provides a measure of cooling effectiveness that can be used to notify maintenance personnel of problems with fans or pumps.
3. Accumulated through-fault monitoring can be an indicator of necessary maintenance, just as accumulated thermal loading can.
4. Combining through-fault, temperature, and other factors can optimize maintenance practices for an overall reduction in total ownership costs.

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INSTALLATION AND MAINTENANCE OF SINGLE PHASE IEC AND EATS STYLE POLE MOUNT TRANSFORMERS

ABB

This document covers the installation and maintenance instructions for single-phase mineral oil-filled pole mount transformers.

1. DISPATCH AND HANDLING

A careful external examination of the equipment should be made by the purchaser's representative when offloading. Any sign of damage must be reported immediately.

The main items to check are:

- The complete unit for any signs of external damage
- The paint work for signs of damage
- The complete unit for any signs of leaks
- The bushings for signs of damage
- The oil level

The equipment should be lifted using the lugs provided for this purpose on the tank walls. Never use points other than those provided for that purpose. When lifting or moving the transformer, care should be taken to ensure that the porcelain bushings and other accessories do not get damaged. The bushings should never be used as handles to move the transformer.

The transformers, when delivered, are fully assembled and ready for installation.

It is not desirable to store the transformers too close to each other, in order to avoid damage to wall mounted bushings and other accessories. Access ways between the rows of stored equipment will allow for checking of oil levels, oil tightness and the condition of the paintwork.

2. INSTALLATION

The transformer should be installed by qualified workmen. Prior to installation check the rating plate of the transformer to ensure that voltage, rating etc are correct for the situation in which it will be used. The transformer is to be fastened to the pole so that the cover of the tank is in the horizontal position. Upper and lower pole mounting brackets are provided for this purpose.

The following checks are also recommended:

- Check with an ohmmeter (or other means) that the windings are in tact. When checking the high-voltage winding, check at each tap position. When checking the low-voltage windings, short circuit the high-voltage bushings and connect them to earth. This is to avoid dangerous high voltages at the high voltage bushing terminals which can be induced due to current flow in the low voltage windings during the checking.
- Check that the off-circuit tap changer is in the correct position (and dual ratio switch if applicable).
- Check that the transformer tank is earthed – an earth flag is provided for this purpose
- Check the tightness of the connections to the terminals. This will help prevent any abnormal heating of the terminals
- Check that the insulators are clean
- Check the oil level. If stored for 6 months or if the storage conditions are bad the dielectric strength of the oil should be checked

3. MAINTENANCE

Very little maintenance is required on single-phase pole mount transformers. We recommend checking the unit ten years after installation and thereafter at intervals of seven years.

Recommended check list for maintenance:

- Oil level – where oil level indicator is fitted. For sealed unit, the oil level will be alright as long as there are no external signs of oil leaks
- Dielectric strength of the oil
- State of the paint work
- Check the value of primary and secondary current, preferably during the period of highest load to ensure the unit is not overloaded
- Check the bushings for signs of damage and clean them

Under conditions of extreme pollution (depositing of dust, salt, chemicals etc) cleaning of the porcelains may be required more frequently.

SAMPLING INSULATING OIL FOR TRANSFORMERS AND OIL CIRCUIT BREAKERS

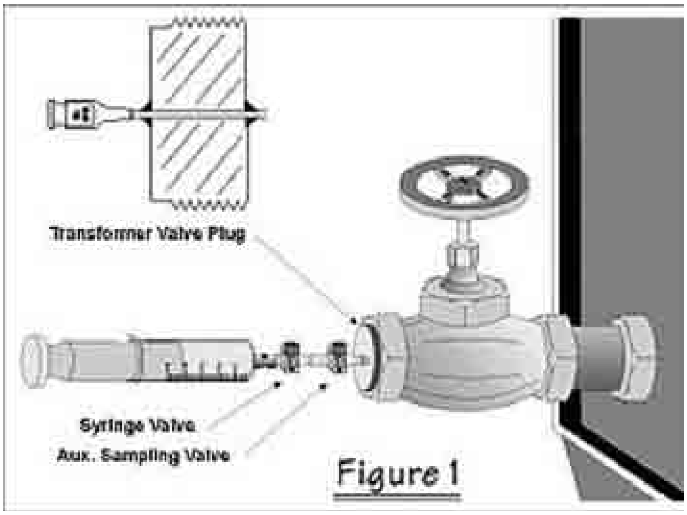
Morgan Schaffer Inc

1- SYRINGE SAMPLING INSTRUCTIONS

GENERAL

The methods outlined here are all based on the use of a single sampling device which can be used to take either oil or gas samples. The sampling device consists of a precision ground 30 cc glass syringe terminated with a Luer-Lok fitting to which is attached a plastic three-way valve. This valve, although removable, is to be regarded as an integral part of the sampling device and any subsequent references to the syringe imply the presence of this valve. A second identical valve, which does not stay with the syringe, is used when taking oil samples. This second valve will be referred to as the auxiliary valve.

Before sampling is commenced the syringe must be either flushed with new transformer oil or pumped vigorously several times with the valve open to eliminate any residual fault gas from the previous sample. The syringe should be examined for the absence of dirt and checked to ensure that the piston slides smoothly.



AUXILIARY FITTINGS

For taking oil samples, an adaptor must be made which can be fitted to the transformer valve and which will accept the tapered inlet of the auxiliary sampling valve. One possibility, shown in Fig. 1, is to epoxy or solder a female Luer hub (cut down from a 15 gauge needle) into a suitably sized hole drilled into the transformer valve plug. Alternatively, a straight 5/32 inch diameter hole drilled in the transformer valve plug will yield an adequate press fit for the auxiliary valve.

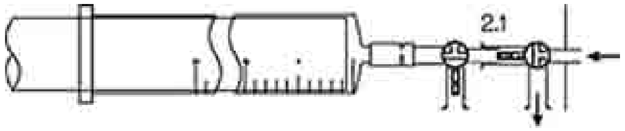
Note, however, that a straight hole can produce scoring and deformation of the plastic valves and hence the syringe valve must never be plugged into a straight hole nor should syringe and auxiliary valves be interchanged. A major function of the auxiliary valve is to protect the syringe valve so that it will stay in good condition for the attachment to the laboratory analysis apparatus.

OIL SAMPLING

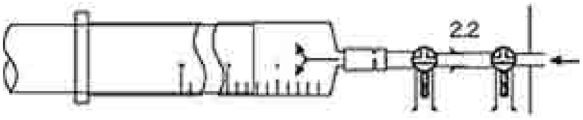
A satisfactory technique for taking bubble-free oil samples is shown in Figs. 1 and 2. The flushing ports of the valves are shown horizontal in Fig. 1 but in practice it is better if they are directed downward to facilitate collection of the waste oil. (Note: the handles of the plastic valves point to the closed port leaving the other two ports in open communication.)

The technique described below requires the oil to be under a slight positive pressure (0.2 psig or greater). A continuous flow is maintained throughout the entire procedure.

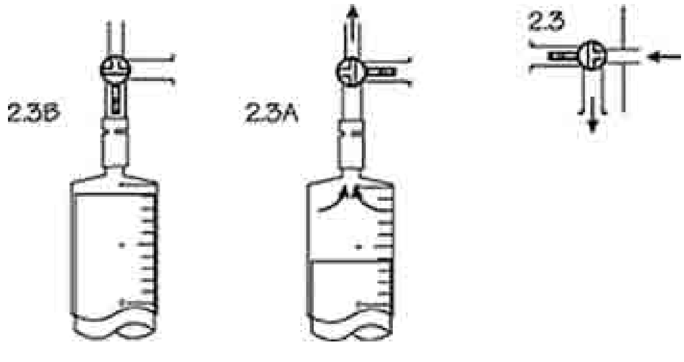
a. Attach the adaptor plug to the transformer valve, then, with its handle in the flush position, plug in the auxiliary valve and allow oil to flush until all trapped air is eliminated. Adjust the oil flow to a suitable rate and then attach the syringe with its valve in the fill position. (Fig. 2.1).



b. Turn the auxiliary valve to the fill position and allow about 10 cc of oil to enter the syringe (Fig. 2.2).

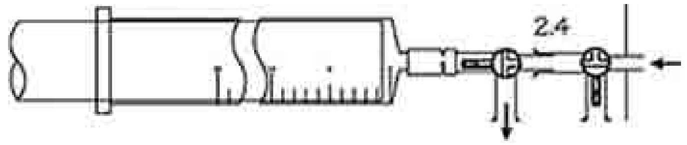


Return the auxiliary valve to its flush position and separate the syringe (Fig. 2.3).



c. With the syringe vertical, eject any air bubbles (Fig. 2.3A) and then depress the piston to the zero mark and close the syringe valve (Fig. 2.3B)

d. The syringe, bubble free and with its dead volume filled with oil, is then re-attached to the auxiliary sampling valve. The auxiliary valve is then turned to the fill position so that oil now flows from the flushing port of the syringe valve (Fig. 2.4).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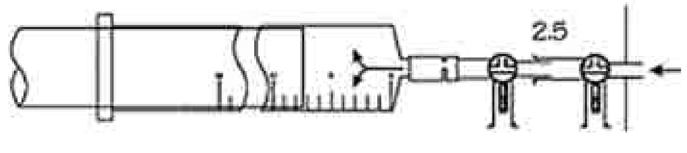
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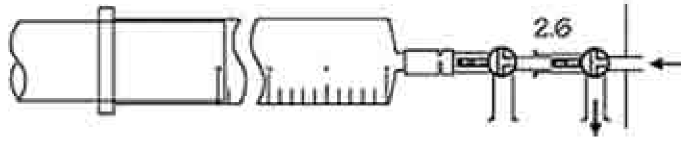

2.6

e. Turn the syringe valve to the fill position and allow oil pressure to push the piston back until the syringe contains approximately 26 cc of oil (Fig. 2.5). Note: if it can be avoided, do not pull the piston manually since this can result in atmospheric leakage and bubble formation. Do not fill the syringe to more than 27 cc to ensure an adequate seal along the piston.

f. Return the syringe and auxiliary valves to their flush positions, separate the syringe and close the transformer valve.

Note: Bubbles may form in the syringe subsequent to sampling because of the different temperature and pressure environment but, provided the sample was bubble free initially, this will not affect the subsequent analysis. No attempt should be made to remove such bubbles.

GAS SAMPLING

With care, somewhat similar procedures can be used for taking gas samples from gas blanketed transformers, but the absence of a visual flow indication can lead to misjudgment of the flow rate resulting in ejection of the syringe piston. The following method is simple and easily controlled. As for oil sampling, it requires the gas to be under slight positive pressure. The only auxiliary equipment required is a short length of 3/16 inch thin wall gum rubber tubing and a 22 gauge hypodermic needle (Both readily available from lab supply houses or from us - free of charge - on request.). No auxiliary valve is needed.

The needle is attached directly to the syringe valve and the rubber tubing attached to the gas sampling valve of the transformer (it is an easy stretch fit on metal tubing from 1/4 inch - 3/8 inch O.D.). The transformer valve is cracked open to allow a slow flow of gas. The actual rate is not critical but, for ease of control and to avoid wasting blanket gas, should be kept as low as possible.

With the syringe valve open, the needle is inserted at an angle through the wall of the rubber tubing and the syringe held in the normal manner with the thumb resting lightly on the end of the piston. The open end of the rubber tube is held in the other hand and, by lightly capping the end with the index finger, gas will be forced into the syringe causing the plunger to be pushed back. The rate of filling is easily and sensitively controlled by finger pressure on the end of the rubber tube. The syringe is flushed once or twice by alternately filling and emptying the syringe while it is still attached to the rubber tube (the tube is, of course, uncapped during the emptying stroke.) On the final fill, the syringe should not be allowed to fill to more than 15 cc to ensure an adequate seal along the piston. The tube is then uncapped, the syringe valve closed and the needle withdrawn from the tube.

When sampling from a gas relay, there is a danger with the above method in losing all the gas before a sample is obtained. This possibility can be eliminated with the following modification of the method.

Close one end of the rubber tube (either with a clamp or by tying the tube in a knot), attach the closed tube to the gas relay sampling valve and the open the valve. Since the pressure in the relay can never be greatly above atmospheric, there is no danger of the rubber tube being blown off. Gas samples can now be withdrawn, without wasting gas, by inserting the needle through the tube wall. Note: this is a static system and it is essential that sufficient gas be discarded (by withdrawing the needle and emptying the syringe) to ensure that the final sample represents gas from the relay and not from the connecting tubing.

SAMPLE IDENTIFICATION

Samples must be identified with a tie-on tag or with an identification labels placed inside the syringe carton. The minimum information required includes syringe serial number, transformer serial number (or company number) and the name and address of the person to whom the report should be sent.

Normally, only one sample is required for a complete analysis but we strongly recommend taking duplicate samples in all critical "one-time" situations where re-sampling at a later date might not be possible or meaningful. These duplicate samples would only be analyzed if data from the first sample were suspect.

SHIPMENT

Syringes should be wiped clean and placed in the syringe cartons as soon as possible after sampling. Unprotected samples must not be allowed to stand around in the light since this can result in further oxidation and breakdown of the oil.

Syringes should be placed in the cartons so that the syringe flange engages the slot in the liner with the flat side of the flange resting against the unslotted side of the liner. This is important to prevent movement of the syringe in transit. If the syringe valve comes in contact with the end of the carton, either by being over-filled or by movement in transit, the glass tip will almost certainly be broken off.

If less than six syringes are sent, the shipping container must be filled out with packing material. To avoid delay and to prevent deterioration or damage, samples must be sent by first class, air mail or air express. Do not ship samples by parcel post.

Sample packs sent from the U.S. should carry green Customs stickers identifying the contents as "Samples for analysis - no commercial value". This will usually eliminate any delay by Canadian Customs.

2- JAR SAMPLING INSTRUCTIONS

a. Sampling should be performed on a sunny day. Do not sample when humidity is above 75%.

b. The oil should be at least as warm as the ambient temperature. Cold oil could condense moisture from humid air and give poor results.

c. The oil sample should be obtained from the bottom drain valve. Do not attempt to sample if the transformer is under negative pressure.

d. The sampling valve must be cleaned prior to sampling.

e. Flush drain valve with sufficient oil to remove stagnant oil from the valve and drain pipe (1/2 to 1 gallon of oil). The oil sample must be representative, that is, oil which is circulating within the transformer.

f. Rinse the jar several times with the oil to be tested before obtaining the actual sample.

g. Fill the 650ml jar 3/4" from the top to allow for oil expansion or contraction.

h. Fill out the information tag completely and attach it to the sample bottle immediately following sampling.

Seal the jar and ship to our laboratories ensuring that the samples are well packaged.

NOTE

1. Do not ship oil with a PCB concentration that is greater than 50 ppm. Please contact Morgan Schaffer if you are sampling equipment that has oil above the 50 ppm limit.

OIL TESTING AND DIAGNOSTICS PREDICTIVE AND PROACTIVE MAINTENANCE - INVESTIGATIVE SERVICES/RESEARCH AND DEVELOPMENT

Kinectrics

Large, critical service power transformers at electrical generating plants must be maintained in excellent condition at all times. Real-time monitoring of electrical and oil characteristics may be required to provide sufficient quality assurance. In contrast, many distribution units may require only occasional dissolved gas monitoring.

AN IDEAL SOLUTION

Kinectrics' state-of-the-art laboratories can provide clients with a full range of transformer fluid and component monitoring services, ranging from routine testing through complex analysis, to large scale R&D testing. Unlike some assembly line testing services, our aim is to provide clients with the solutions they need—not just "more data". Convenient testing packages tailored to clients' requirements and interpretation of data can be provided.

Additional services for advanced work at our Kinectrics' site include high voltage testing facilities for large-scale electrical testing and environmental laboratories for biodegradation and toxicity testing.

DIELECTRIC FLUIDS AND GASES

The Petroleum Products Group of Analytical Chemistry (PPG) provides routine testing, consulting and R&D services for dielectric fluids and related materials in support of electrical equipment operation, preventive maintenance and problem solving. The PPG provides early warning of incipient fault conditions and is a technical resource centre for specifications, product recommendations, materials compatibility testing, materials property information and the interpretation of test data. Our expertise includes consulting on dielectric fluid monitoring practices, equipment life extension through the use of novel and advanced materials or procedures, and the identification and resolution of tribology (wear/friction/sticking) problems in lubricated components of electrical systems or equipment.

Our laboratory is registered to ISO 9001 and quality controlled—result quality and accuracy are assured. Sample tracking is computerized and test data are managed electronically by a powerful Oracle-based Laboratory Information Management System (LIMS). Electronic data reporting can be customized to suit the client. In addition, standard oil test data can be provided in Transformer Oil Analyst (TOA) spreadsheet format and electronically ported to the client.

Kinectrics' PPG areas of expertise include:

- **Routine condition monitoring and advice** - Approximately 30 ASTM and industry standard tests pertaining to dielectric fluids are routinely supported in our laboratories
- **Dissolved gas analysis, including furans, phenols and interpretation** - Rapid, accurate fault gas analysis is available on a routine basis for oils, silicones and askarels (PCBs).
- **Analysis of SF6 gas, and interpretation** – SF6 analysis and data interpretation and diagnostic services. Databases are maintained for trend analysis.
- **Askarel (PCB) monitoring** - High PCB content dielectrics can be monitored for dissolved gas and other standard properties as well as sophisticated determinations such as PCB/chlorobenzene ratio.
- **"Green" Issues, PCB Contamination Issues** - Waste management, oil identification, spill cleanup, PCB contamination measurement, fluid reclaiming/recycling/reinhibiting, environmentally friendly materials, and disposal issues can all be addressed.
- **Lubrication Issues** – Advice on the selection of switchgear or other lubricants and hydraulic fluids, and microsample testing techniques for predictive maintenance applications is available.
- **Investigative and R&D services** – Areas covered include: equipment life extension, accelerated aging and life studies, new materials, flammability assessments, failure studies, experimental winding model tests, filter evaluations and

detailed analysis of deposits or materials

- **Advanced analysis** – Comprehensive laboratory services are available for general and advanced analytical tests such as furanic material components and oil additives by HPLC and trace analysis of degradation products and contaminants by GC-MS, EDX, AES or other techniques.

CHOOSING THE RIGHT MAINTENANCE STRATEGY

Most choices are variants of four basic approaches.

- **Breakdown Maintenance** - Nothing is done until the electrical equipment fails
- **Scheduled Maintenance** - Inspections, replacements, reconditioning and repairs are scheduled, hopefully ahead of anticipated failures
- **Predictive Maintenance** - A strategy based on routine monitoring, where the aim is to detect and monitor incipient faults before breakdown occurs or expensive repairs are required
- **Proactive Maintenance** - An advanced form of maintenance where root causes of failure are identified and routinely monitored

SEISMIC EVALUATION OF 196 KV PORCELAIN TRANSFORMER BUSHINGS

Juan Chavez and Amir Gilani

The reliability and safety of electrical transmission and distribution systems after an earthquake depend on the seismic response of individual substation components such as transformer bushings. Post earthquake reconnaissance of electrical substations has identified porcelain transformer bushings as being particularly vulnerable to severe earthquake shaking.

In 1997, the Pacific Gas & Electric (PG&E) Company sponsored a research project to investigate the seismic response of 196 kV porcelain transformer bushings during moderate and severe earthquake shaking. Two identical 196 kV bushings, manufactured by Asea Brown Boveri (ABB) of Alamo, Tennessee, were tested on the earthquake simulator at the Pacific Earthquake Engineering Research (PEER) Center using levels of earthquake shaking consistent with those adopted for seismic qualification and fragility testing of electrical equipment. Bushing-1 (fig. 1) was designated for qualification testing, and Bushing-2 was designated for fragility testing. The principal investigators for the study were Professor Gregory Fenves and Dr. Andrew Whittaker, with assistance from research engineers Juan Chavez and Amir Gilani.

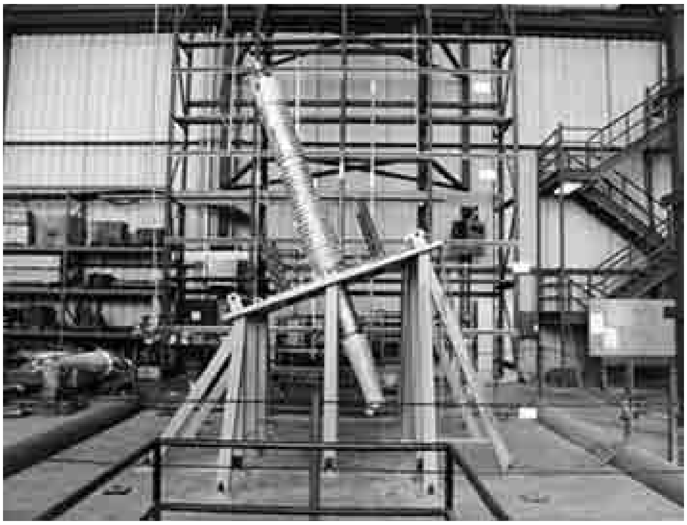


Fig. 1. Bushing-1 installed in the mounting frame prior to testing.

Bushings are qualified using a standard developed by the Institute of Electrical and Electronic Engineers (IEEE 693). The draft IEEE standard (IEEE 1997) details procedures for qualification of electrical substation equipment for different seismic performance levels. The objective of fragility testing is to establish a relation between limiting states of response (e.g., gasket failure, cracking of porcelain) and peak ground acceleration for a selected piece of equipment.

BUSHING DESCRIPTION

A longitudinal cross section of a 196 kV bushing is shown in figure 2.

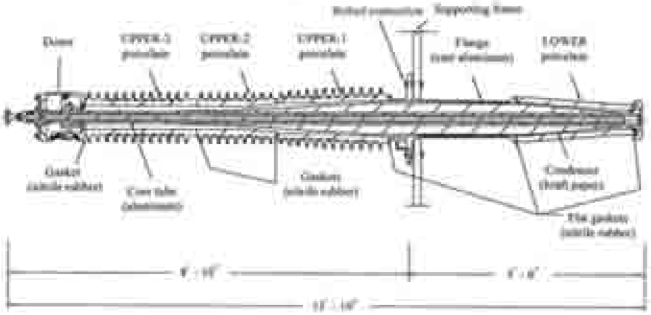


Fig. 2. Geometry and longitudinal section of a 196 kV transformer bushing

The overall length of the transformer bushing is 166 in. (4.2 m). The segment of the bushing above the cast aluminum flange plate is 106 in. (2.7 m) long and includes three porcelain insulator units and a metallic dome at the top of the bushing. The porcelain units, the cast flange, and the metallic dome are separated by gaskets made of nitrile rubber. The segment of the bushing below the flange plate includes the extension of the cast aluminum flange plate and one porcelain insulator. The flange plate, which is used to connect the bushing to the transformer, is cast with two lifting lugs to facilitate movement and installation of the bushing.

A cross section of the bushing shows an aluminum core housing the copper cables that provide the electrical connection, a multilayered kraft paper condenser wrapped around the core, an annular gap between the porcelain and condenser that is filled with an oil to provide electrical resistance, and a porcelain insulator. The bushing is post-tensioned along its longitudinal axis through the aluminum core with a force of 27 kip (120 kN). Springs in the metallic dome ensure a uniform distribution of compression around the perimeter of the porcelain units and the gaskets. The weight of the bushing is approximately 1,050 lb (4.7 kN).

EARTHQUAKE SIMULATOR TESTING

The earthquake testing was performed on the earthquake simulator at the Pacific Earthquake Engineering Research Center. The bushings were mounted on a support frame that was designed to be rigid. The mounting plate in the frame was sloped at 20 degrees measured to the vertical because a bushing qualified at this angle is deemed by IEEE 693 to be qualified for all angles between vertical and 20 degrees measured to the vertical (fig. 1).

The instrumentation scheme followed the IEEE 693 requirements. Accelerations and displacements of the earthquake simulator platform, of the mounting frame, and of the top, midheight, and bottom of the bushing were measured. Strain gages monitored the axial strains in the porcelain unit above the flange support. Displacement transducers measured displacements across the gasket (located immediately above the flange) parallel to the axis of the bushing.

EARTHQUAKE HISTORIES FOR TESTING

The experimental program for the two 196 kV transformer bushings consisted of low-amplitude unidirectional resonant search (banded white-noise and sine-sweep) tests and triaxial earthquake-history tests. The resonant search tests were performed to determine the dynamic characteristics (modal frequencies and damping ratios) of the bushings. The fundamental resonant frequencies were 15.5 Hz in the longitudinal (local x-direction) and 14.1 Hz in the lateral (local y-direction). The corresponding damping ratio was approximately 2.5 percent. Modal data could not be determined in the vertical (local z-direction) of the bushing.

The earthquake histories used for the qualification and fragility testing were developed using two recorded (three-component) sets of near-field ground motion records: Tabas (1978 Iran earthquake) and Newhall (1994 Northridge, California, earthquake). These records are representative of earthquakes known to have a high potential for damaging building structures and equipment. The acceleration records were modified using a nonstationary response-spectrum matching technique developed by Abrahamson (1997) to match the IEEE target spectrum for testing, and they were further high-pass filtered using a cut-off frequency of 1 Hz so as not to exceed the displacement limit of 5 in. (127 mm) of the earthquake simulator. The removal of low-frequency input has little to no impact on the dynamic response of the bushing.

For Moderate Performance Level, IEEE 693 permits equipment to be tested using accelerations compatible with the Required Response Spectrum (RRS) shown in figure 3 (accelerations with a peak ground acceleration of 0.25 g).

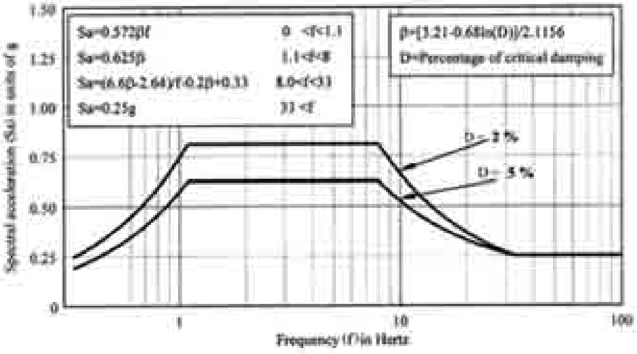


Fig. 3. Required response spectrum (RRS) for Moderate Performance Level

For High Performance Level, the ordinates of the target spectra are twice those of the spectra for Moderate Level qualification. To account for the amplification of earthquake motion due to the influence of the flexibility of the transformer near the bushing mount, the ordinates of the preceding target spectra are amplified by a factor of two. To check porcelain stresses and oil leakage, the ordinates of the target spectra are further amplified by another factor (of safety) of two. Therefore, for Moderate Level qualification testing, the earthquake histories were matched to the IEEE spectra with peak acceleration of 1.0 g.

MODERATE LEVEL QUALIFICATION OF BUSHING-1

Bushing-1 was designated for seismic qualification testing. Tabas1g (Modified Tabas record with a nominal peak ground acceleration of 1.0 g) was selected for the Moderate Level seismic qualification of Bushing-1. Figure 4 shows the measured and target spectra (for 2-percent damping) in the longitudinal direction.

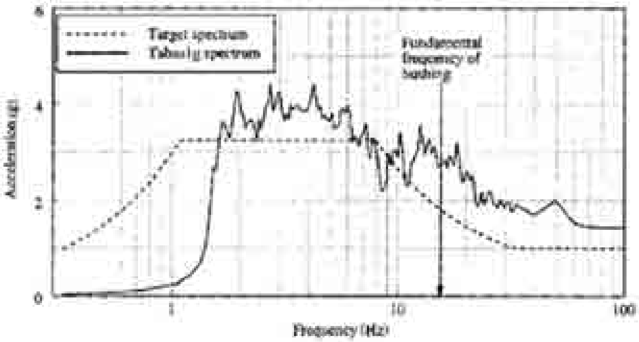


Fig. 4. Response spectra (2-percent damping) for Bushing-1 Moderate Level qualification test in the longitudinal direction.

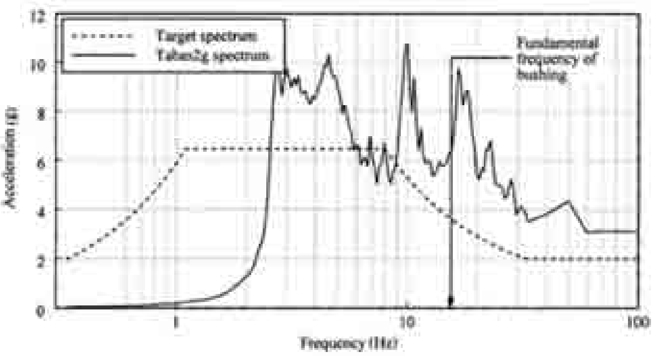
The spectral ordinates associated with the response histories of the mounting frame exceed those of the target spectrum due to the response interaction along the three axes of the earthquake simulator and due to some rigid body rotation of the platform observed during the tests. The maximum porcelain strains were less than 1 percent of the ultimate strain, and there was no evidence of oil leakage.

HIGH LEVEL QUALIFICATION OF BUSHING-2

Bushing-2 was designated for fragility testing, and it was also used for High Level qualification (the ordinates of the target horizontal and vertical spectra are twice those of the spectra used for Moderate Level qualification). Tabas2g (modified Tabas record with a nominal peak ground acceleration of 2.0 g) was used for the High Level qualification.

As shown in figure 5, the spectral ordinates associated with the longitudinal response of the mounting frame during the test exceeded those of the target High Level spectrum (for 2-percent damping) in the frequency range of interest (10 to 20 Hz).

Fig. 5. Response spectra (2-percent damping) for Bushing-2 High Level qualification test in the longitudinal direction



The mounting frame was designed to be rigid and thus not amplify the motions of the earthquake simulator. However, amplification of the horizontal motion for frequencies between

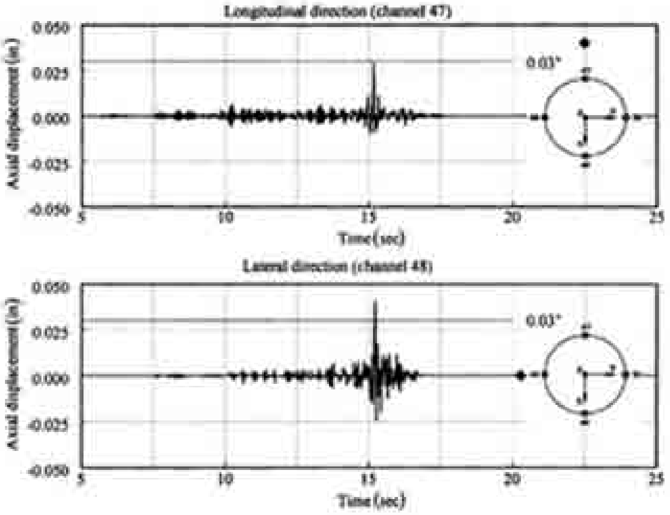
10 and 20 Hz was observed during the tests. The Tabas2g test produced no external damage in Bushing-2. The maximum porcelain strain was approximately 2 percent of the ultimate strain, and there was no evidence of oil leakage. The maximum relative displacement between the bushing and the mounting frame was 0.50 in. (13 mm). The maximum total acceleration at the upper tip of the bushing exceeded 6.0 g.

FRAGILITY TESTING OF BUSHING-2

Both the Tabas and Newhall earthquake histories were used for the fragility testing of Bushing-2. The Tabas and Newhall earthquake histories were used for simulations with target peak accelerations of less than 1.0 g; the Tabas histories were used for target peak accelerations greater than 1.0 g. After each earthquake test, the response data were analyzed, the bushing was inspected for damage and oil seepage, and the bolts joining the bushing flange plate to the adaptor plate and the adaptor plate to the mounting plate were checked for tightness. All bolts that were found to be loose were retightened using a calibrated torque wrench.

Tabas2g+ (modified Tabas record with a nominal peak acceleration greater than 2.0 g) was the last test of Bushing-2. The peak acceleration response of the mounting frame in the longitudinal direction was 2.7 g. This represents the limit state for the fragility curves of this bushing. During this test, oil leaked from the gasket immediately above the flange plate. The peak accelerations at the upper tip of Bushing-2 exceeded 6 g. Figure 6 shows the vertical displacement of the porcelain unit (above the flange) relative to the flange plate, as measured at two locations around the circumference of the bushing.

Fig. 6. Relative vertical displacement histories across gasket between porcelain and flange plate at the end of fragility test for Bushing 2.



A relative displacement of 0.03 in. (0.8 mm)- the limiting value established by the manufacturer, ABB, for probable oil leakage- was reached only once in the lateral direction. Given that the duration of the gasket opening was extremely short, it is not surprising that the loss of oil was tiny. Following earthquake testing, the bushings were returned to the ABB facility in Tennessee for disassembling and electrical testing. Both bushings passed the requisite IEEE electrical tests, and there was no evidence of structural damage to the bushings.

CONCLUSIONS

Both 196 kV transformer bushings survived the effects of severe earthquake shaking. Bushing-1 passed the requirements for Moderate Level qualification, and Bushing-2 met the requirements for High Level qualification. Bushing-2 was subjected to several earthquake simulations with input accelerations exceeding 1.0 g, and suffered no visible damage until after the last earthquake test: a simulation that generated input accelerations of 2.7 g (longitudinal direction), 2.9 g (lateral direction), and 1.2 g (vertical direction). Therefore, the 196 kV ABB transformer bushings are expected to perform well in extreme loading environments.

ACKNOWLEDGMENTS

The research was sponsored by the Pacific Gas & Electric Company. The porcelain bushings were fabricated by Asea Brown Boveri.

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BENEFITS OF SENSORS FOR ONLINE MONITORING SYSTEMS FOR POWER TRANSFORMERS

Par S. Tenbohlen, T. Stirl, M. Rösner, Alstom T&D

To increase availability and to achieve opti-mised operating management, on-line condition monitoring for power transformers is useful and necessary. Based on the experiences with a considerable number of systems in operation, a generally applicable set-up of sensors is proposed. Furthermore the method of data acquisition, analysis and distribution by using a modern monitoring system connected to the internet is described.

By means of mathematical models, the acquired measured data are converted to useful information for a reliable condition diagnosis. The evaluation of data acquired on-site shows the capability to detect problems before they result in major failures. In particular algorithms for the calculation of overload capacity are becoming increasing importance.

1 INTRODUCTION

Transformer outages have a considerable economic impact on the operation of an electrical network. Therefore, it is the aim to ensure an accurate assessment of the transformers condition. Techniques that allow diagnosing the integrity through non-intrusive tests can be used to optimize the maintenance effort and to ensure maximum availability and reliability. With the increasing average age of the transformer population, there is an increasing need to know the internal condition. For this purpose on- and off-line methods and systems have been devel-opedover the years. On-line monitoring can be used continuously during the operation of transformers and offers, in that way, a possibility to record different relevant stresses which can affect the lifetime. The automatic evaluation of these data allows the early detection of an oncoming fault. In order to enable a consistent utilization of the technically possible load capacity of the transformer, statements regarding the current over-load capacity, for example, can be made.

2 DESCRIPTION OF MONITORING SYSTEM

2.1 SENSOR SET-UP

A multitude of different measurable variables can be collected for on-line monitoring [1]. However, it is very rarely useful to use the entire spectrum. Therefore, sensor technology must be adjusted to the specific requirements of a particular transformer or transformer bank, depending on age and condition. From experience with more than 150 monitoring systems, the following general set-up of sensors (for example) is proposed for the use with a 400 kV power transformer:

(1) PT100 for measurement of top oil temperature
(2) PT100 for measurement of ambient temperature
(3) C.T. for measurement of load current (single phase)
(4) Measurement of voltage at measurement tap of bushing (three phase)
(5) Measurement of oil pressure of bushing
(6) Sensor for measurement of oil humidity
(7) Sensor for measurement of gas-in-oil content
(8) Tap changer position
(9) Power consumption of motor drive
(10) Digital inputs for switching status of fans and pumps

2.2 ARCHITECTURE

With the Alstom monitoring system MS 2000, the outputs of the above-mentioned sensors are wired onto field bus terminals in the monitoring module installed at the transformer. Within these data acquisition units the analogue signals are digitized and sent via a field bus to the monitoring server. By means of this industrial proven technology, it is possible to monitor all transformers in one substation with a single system which is extremely cost effective. The erection of the server in an operating building offers the advantage that the ambient conditions (e.g. temperature, vibrations) are much more suitable for a PC. The connection to the protection and control system can be done either by dry relay contacts or a digital protocol according to IEC 60870-5-101 /1,2/.

2.3 DISTRIBUTION AND VISUALIZATION OF MONITORING DATA

In order to prevent outages and save maintenance expenditures, on-line monitoring systems are installed at the main equipment of the substation (power transformers, circuit breaker, disconnectors). The access to the monitoring data should be done by means of a standardized platform(Internet Explorer). This eliminates the need to install individual software on each desktop PC.

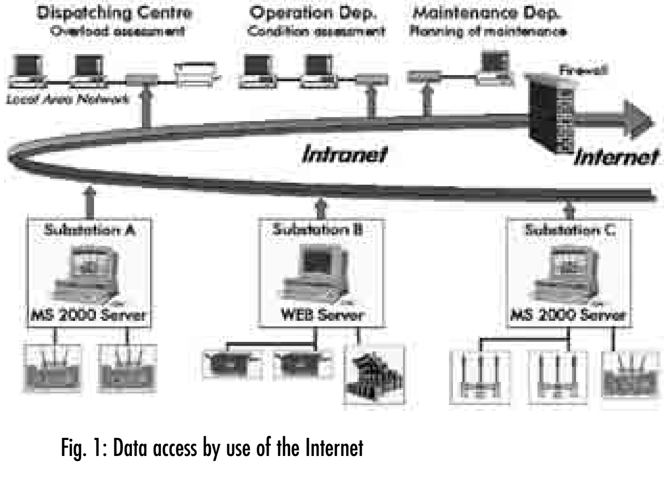


Fig. 1: Data access by use of the Internet

The user must have easy and safe access to all necessary information about the installed electrical equipment. This means that not only power transformers,but also GIS, circuit breakers and disconnectors are of fundamental importance [3].

The dispatching centre should be informed about loading capacity (overload calculation).

The operation and maintenance department should perform condition assessment and plan maintenance procedures exactly (Fig. 1). This wide distribution of information can be done by a web-based solution. An additional module installed on the monitoring server allows generating HTML-based web pages, which show both on-line and historical data (Fig. 2). If the monitoring server is connected to the local area network (Intranet) of the utility, all departments will receive the necessary information. Therefore, the number of users directly connected to the monitoring server is practically unlimited. Password protection gives only specific users the right to data access. through use of a firewall, it is also possible to have access to the complete substation by use of the Internet.

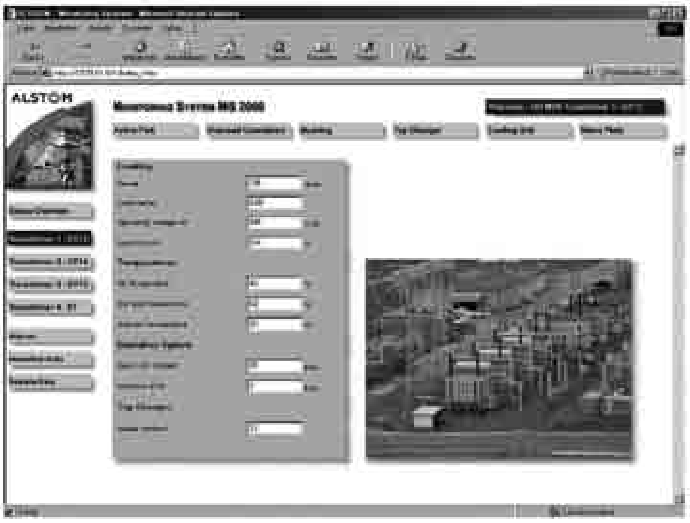


Fig. 2: Web-based visualization of transformer condition

3 PRACTICAL EXPERIENCES

Initially, on-line monitoring was characterized by the use of some individual sensors which were dedicated to monitor only a small part of the power transformer. For example, a hydrogen sensor is used to detect problems within the active part such as partial discharges or hot spots. The philosophy of concentration on a specific part of the transformercame as a result of individual experience with specific failures within an utility. For example, if a utility experienced problems with bushings, the main effort was concentrated on the diagnostic of bushings. But the analysis of reasons for failures of a larger population of transformers than those of a single utility showed that major failures occur in all parts of the transformer [16]. So, the need to have a comprehensive system which not only monitors the active part but also other important and components such as on-load tap changers and bushings is understand-able. In recent years the monitoring system MS 2000 has been installed worldwide at power transformers of all major manufacturers. At first, utilities tested the system with grid-coupling transformers of minor importance. Due to positive experience, this system is now operating in such strategically important areas as nuclear power stations, pumped storage power stations, coal power stations and aluminium industry. Most of these installations were retrofitted on-site at aging transformers. Normally the installation of sensors requires no welding at the transformer and takes about two days. The transformer has to be taken out of operation only for half a day to install the voltage sensors and the tap changer monitoring module.

3.1 ACTIVE PART

For early failure detection, monitoring of the active part is of particular importance. It is fundamental to measure the electrical variables load current and operating voltage directly at the transformer. A bushing-type current transformer is used for load current measurement. The load current and top oil temperature are the starting variables for the calculation of hot-spot temperature according to IEC 60354 and aging rate of active part insulation [5]. This enables the evaluation not only of information regarding lifetime consumption but also of the temporary overload capacity of the trans-former [4]. For proper assessment of the mechanical condition of the windings, the number and amplitude of short circuit currents is of tremendous importance. These are detected and evaluated by using a high sampling rate for the load current signal.

3.1.1 GAS-IN-OIL AMOUNT

For the gas-in-oil detection, a Hydran sensor is used which reads a composite value of gases in ppm (H_2 (100%), CO (18%), C_2H_2 (8%), C_2H_4 (1,5%)). As hydrogen is a key gas for problems in the active part, an increase in the output signal of the sensor is an indication of irregularities such as partial discharge or hot spots [6]. The evaluation of this measuring signal, together with the dependency on the temperature of the oil and the load current, provides a reliable basis for the continuous operation of the transformer. In the event of an increase of gas-in-oil content, immediate action can be taken via an off-line dissolved gas analysis (DGA) to determine the concentration of other components dissolved in the oil in order to clarify the cause of the potential damage.

In Fig. 3 the gas-in-oil amount of an 80 MVA grid coupling transformer for an aluminium plant is shown for the time interval of one year. The monitoring system detected an increase of gas-in-oil content. The reason was assumed to be the temperature increase during the summer. A DGA performed in August revealed a CO content of 427 ppm of CO and 27 ppm of H_2 which is in accordance with the output of the Hydran sensor (108 ppm). So the reason for the increased gas-in-oil content was the increased value of CO, which was generated because of the normal increase of oil temperature. Thus, for exact interpretation of the Hydran signal awareness of load and temperature is required.

3.1.2 OIL HUMIDITY

A capacitive thin film sensor is used for accurate calculation of aging rate. As the transformer warms up, moisture migrates from the paper into the oil. From this equilibrium of moisture in oil and paper, the water content in the paper can also be calculated by the monitoring system [8, 9]. This value is required for calculation of the emergency overload time. Moisture in paper restricts the loading capacity because of the risk of bubble emissions. Also, the release of water drops from winding paper to oil can occur. So the acceptable limit for the hot spot temperature is dependent on the water content in the paper [10].

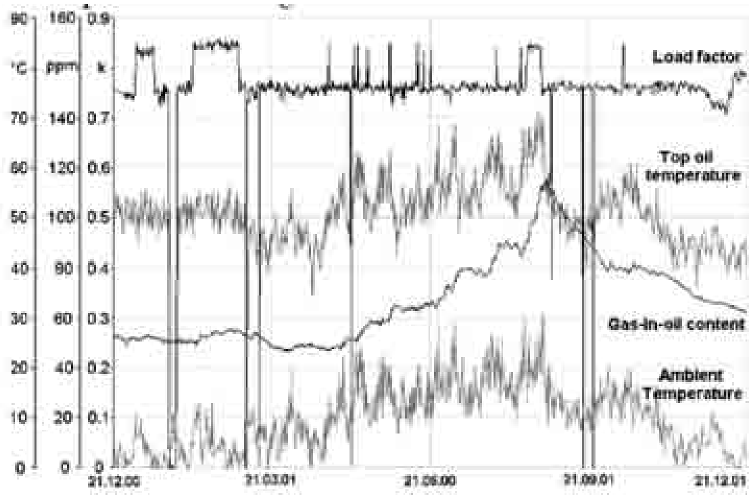


Fig. 3: Gas-in-oil amount dependent on load and top oil temperature of a 80 MVA grid transformer

3.2 BUSHINGS

3.2.1 DETECTION OF OVERVOLTAGES

The voltage applied to the transformer is acquired at the measuring tap of the capacitor bushing by means of a voltage sensor. It acts with the capacity of the bushing as a voltage divider. This enables not only the measurement of the operational voltage but also the detection of overvoltages because, due to its design, the voltage sensor has a bandwidth up to MHz. The output of the voltage sensor is connected to a peak sampler to detect the amplitude of overvoltages by the monitoring system. Overvoltages represent an essential risk poten-tial for the insulation of transformer windings. Taking into account the volume of noxious gases which are dissolved in oil, deductions can be made about the possible damage to the insulation of the active part after the occurrence of overvoltages.

3.2.2 CHANGE OF CAPACITANCE

Failure of condenser bushings occurs often because of partial flashover of the metallic foils which are used for controlling the electrical field within the bushing. Such partial flashovers do not lead to a sudden failure of the bushing, but they grow from layer to layer until the voltage stress of the remaining layers is so high that complete breakdown occurs. If a partial flashover of one layer occurs, the capacitance of the bushing will be increased by DC (Table 1).

Voltage [kV]	Number of foils	DC
123	28	3.6 %
245	42	2.4 %
400	60	1.7 %
550	70	1.4 %

Table. 1: DC for partial flashover of one layer for oil-impregnated bushings /9/

The change of the capacitance DC of the bushings can be detected by the monitoring system by comparing the output of one voltage sensor with the average value of the other two phases.

The result is processed by averaging algorithms to eliminate imbalances of the grid voltage and variations due to temperature changes. This is assumed to be possible because the deterioration process normally has a considerable longer time constant. This triggers an alarm and a warning.

In Fig. 4 the change of capacitance of a 400 kV grid coupling transformer is shown for a time interval of two months. It can be seen that variations due to unbalanced voltages and temperature variations are in the range of 0.4 %. The signal-to-noise ratio is, therefore ,sufficient to assess the insulation condition reliably. At a warning level of 1%, the monitoring system triggers a message for inspection of the bushing.

3.3 ON-LOAD TAP CHANGER

An important component of a power transformer and also a frequent reason for severe failures is the on-load tap changer [13]. Therefore the monitoring of this highly stressed element is a necessity.

3.3.1 TAP CHANGER POSITION

Recordings of the tap changer position and the operating current help to determine the number of tap switching operations and the total switched current. As the contact wear of the diverter switch contacts is a function of the switched load current, this information is needed to perform condition-based maintenance for the diverter switch [14]. If an excessive wear situation is undetected, the contacts may burn open or weld together. To avoid these problems, limiting values for the time in service, number of operations and total switched load current can be pre-set in accordance with maintenance instructions of the OLTC manufacturer.

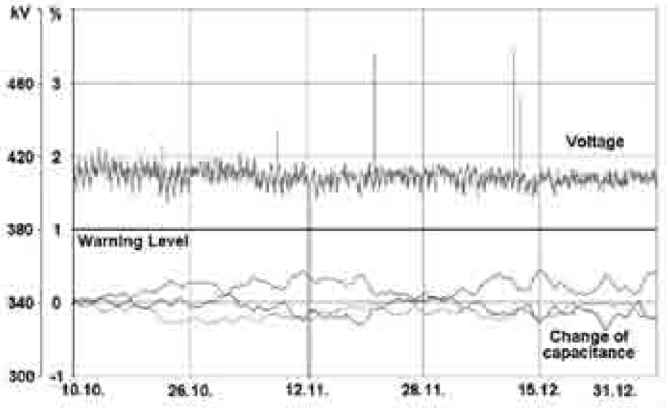


Fig: 4: Voltage and change of capacitance of 400 kV bushings

3.3.2 ASSESSMENT OF MECHANICAL CONDITION

OLTC failures are often dominated by mechanical faults in nature. Such defects can be, for example, broken linkage, failure of springs, binding of contacts, worn gears and problems with the drive mechanism [15]. Mechanical and control problems can be detected by measurement of the power consumption of the OLTC drive, because additional friction, extended changer operation times and other abnormalities have a significant influence on the drive current. An event record of power consumption is captured during each tap changing proc-ess and analyzed by evaluation of 6 characteristic parameters which are:

1. Time of inrush current:

The inrush current flows during a period of about 300 ms. It is related to the static friction and backlash in the linkages.

2. Total switching time:

Variation of time required for a tap changing process indicates problems with the control of the OLTC.

3. Power consumption index:

The energy consumed by the motor drive during a tap changing process divided by the total switching time is represented as the power consumption index. This value is dependent on the operation temperature and characterizes the average running conditions.

4. Maximum sector 1 (*S1*):

During the motion of the selector contacts, the amplitude of the power consumption is monitored. This value represents the maximum during opening and moving of the selector contacts.

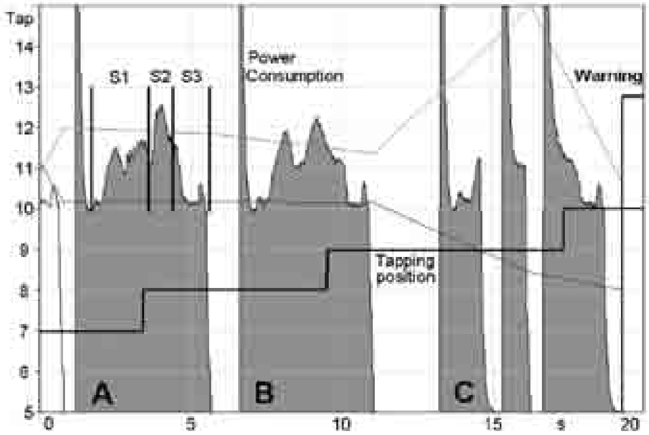
5. Maximum sector 2 (*S2*):

This value is the maximum during the closing of the selector contacts.

6. Maximum Sector 3 (*S3*):

The amplitude of the power consumption is recorded during diverter switch action. These six parameters characterize each tap changing process, and in case of deviations, warning messages are generated. In Fig. 5 such a situation is presented for three successive tap changing processes recorded during maintenance of the OLTC. The first two signatures (A, B) show a regular tap changing process. The peaks on the curves are caused by the friction of opening, revolution and closing of selector switch [2]. Because tap changing process C differed significantly from normal tap changing, the parameters for total switching time, maximum sector 2 and 3 and power consumption index showed abnormal variations. Based on this the monitoring system sent an alarm message to the appropriate engineer. The root cause analysis revealed that, during the tap changing process C, the handcrank was inserted into the drive mechanism which interrupted the process and therefore triggered the warning message. So, this problem was caused by incorrect operation and was not an internal problem, but this event illustrates the capabilities as an early warning system for mechanical anomalies.

Fig. 5: Faulty tap changing process



3.4 COOLING UNIT

3.4.1 THERMAL RESISTANCE

The thermal resistance Rth describes the efficiency of the cooling unit. For air-cooled power transformers, the actual thermal resistance can be calculated by the following equation:

$$R_{th,act} = \frac{\vartheta_{oil} - \vartheta_{air}}{P_0 + P_{k,n} \cdot k^2}$$

The result has to be averaged to eliminate variations due to the dynamic behavior of load factor oil and ambient temperature. Furthermore, the number of fans and pumps in operation has to be taken into account to calculate the nominal thermal resistance Rth.

On-line monitoring of the cooling unit of a 420kV/600MVA grid-coupling transformer by calculation of the nominal thermal resistance Rth showed a strong increase after switching on two additional fans which. This was signaled by the control system (Fig. 6). This increase triggered a warning message by the monitoring system. A local check in the substation revealed that, due to a failure of energy supply, only half of the cooling unit (3 fans) was in operation and therefore only three fans were running. This status was not in accordance with the information of the control system and led to the strong increase of nominal thermal resistance. With the present load and half of the cooling power the transformer could be kept in service. But it would not be possible to operate the transformer with nominal load due to the missing cooling power. This scenario shows the importance of detecting minor failures.

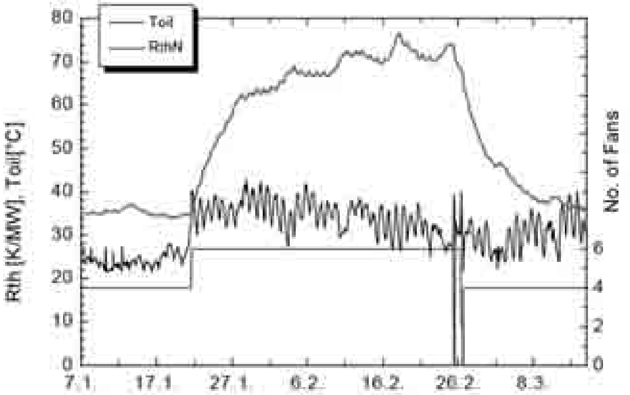


Fig 6: Abnormal condition of cooling unit detected by increase of thermal resistance Rth

4 CONCLUSIONS

The justification for on-line monitoring of power transformers is driven by the need of electrical utilities to reduce operating costs and enhance the availability and reliability of their equipment. The evaluation of data acquired by an on-line monitoring system shows the capability to detect oncoming failures within active part, bushings, on-load tap changer and cooling unit. Using the benefits of modern IT-technology, the distribution of information about the condition of the equipment can easily be done by means of standardized web browser technology.

When considering the size of on-line monitoring systems, importance and condition of a power transformer have to be analyzed, especially for aged transformers. In general, at strategic locations in the electrical network on-line monitoring is necessary and valuable because, by the prevention of major failures, costs for outages, repair, and associated collateral damages can be minimized.

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TWO-DIMENSIONAL SHAKING TABLE TEST OF TRANSFORMER BUSHING WITH SEISMIC ISOLATION DEVICE

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ABSTRACT

Recent and past destructive earthquakes have caused significant loss to the power transmission industry. One typical failure of the electrical power system is the cracking of the mounted porcelain bushing. This paper presents a study in which a 146 kV ceramic electrical transformer bushing was mounted onto a simulated transformer body and tested on a 2D shaking table for response to different types of ground motions. A wire-rope isolation system called WEAR was installed between the transformer body and the bushing to reduce the effect of earthquake forces on the bushing. This research found that the WEAR system was generally effective in reducing the peak acceleration at the top of the bushing.

BACKGROUND

Damages to power transformers of substations by recent destructive earthquakes have prompted for the need to find a way to seismically retrofit transformers. The most vulnerable part of the whole transformer system is the mounted porcelain bushing, mainly because porcelain is a brittle material and has almost no energy-absorbing capabilities. Failure of the bushing includes oil leak from connection-interface of transformer/bushing or the fracture of the porcelain body itself. Different proposals have been made to mitigate the effect of earthquake motions on this system. One proposal by Murota is to isolate the entire transformer system with rubber and sliding bearings [1]. In this research, an isolation device called wire-rope isolation system (WEAR) was used to separate the bushing from the transformer frame while a viscous base damping system was installed beneath the transformer to simulate the effect of the oil inside the transformer.

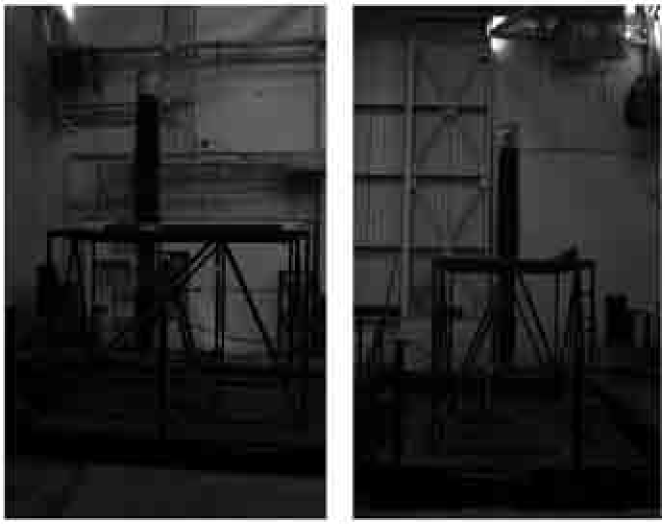
OBJECTIVES

The objectives of this research are:

1. Analyze the effect of different earthquake motions on a 146 kV electrical transformer bushing.
2. Evaluate the effectiveness of the WEAR isolation system

METHODS

In this experiment, a 146 kV bushing was mounted onto a simulated transformer body as shown in Figure 1. The transformer frame was constructed of A500 Gr. B HSS2x2x5/16 tubing seal-welded at all joints. The top plate was made from _ inch A36 plate material. The bushing was placed into a 14-inch diameter hole made specifically for it. The placement of the bushing is such that it provides the most flexible mounting position away from all the supports. The bushing was instrumented with triaxial accelerometers at relevant positions along its length (See Figure 2 for more details). A viscous base damping system was installed right underneath the bushing. The connection of the bushing to this device simulates the effect of oil acting on the bushing. The total weight of the bushing is 996 lbf. In the unprotected condition, the bushing was connected to the top plate of the transformer frame by twelve 1-inch UNC high strength bolts, which were lubricated and torqued to 50 ft-lbf.



a) East View b) North View

Figure-1 Simulated Transformer with Mounting Bushing

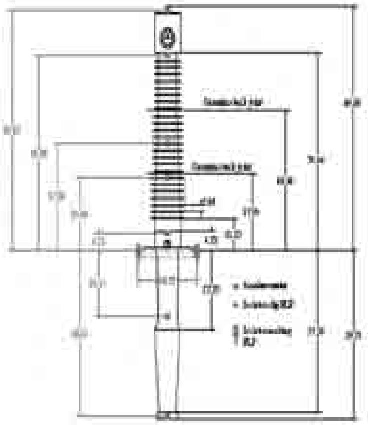
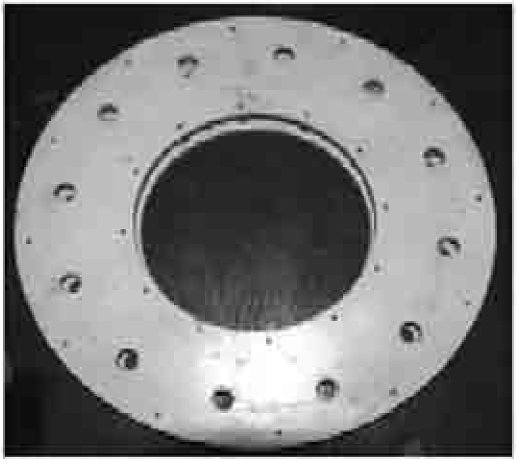


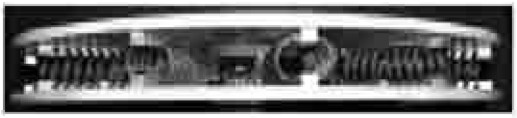
Figure-2 Accelerometer Layout

The wire-rope isolation system was fastened to the top plate and mounting flange with 1 inch UNC bolts lubricated and torqued to 50 ft-lbf. Figure 3 shows the plan and elevation view of this system. The system was subjected to nine ground motions supplied by the UC Irvine Bi-Axial Seismic Simulator (UCI-BASS). These ground motions include the 1940 El Centro, the 1994 Northridge-Sylmar, and the artificial ground motion matching the IEEE design spectrum.

They represent a wide range of frequency characteristics and were scaled to different intensity levels. The specimen was tested under three different mounting conditions: WEAR-isolated with and without viscous base dampers and unprotected.



a) Plan View



b) Elevation View

Figure 3: WEAR Isolation System

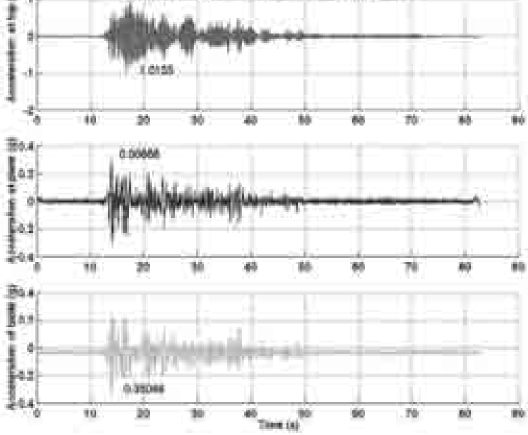


Figure 4: Time History for El Centro NS-Up with no protection

RESULTS

The time history graph shows that the WEAR protective system does, in fact, reduce the peak acceleration of the bushing. For example, Figure 4 displays the time history of the table, plate, and top of bushing for the unprotected case of El Centro N-S. Similarly, Figure 5 shows the corresponding data for the WEAR-protected case. The protective system significantly reduced the peak ground acceleration for the bushing from 1.02 g to 0.289 g. This similar reduction was observed for all of the ground motions tested. Figure 6 shows the peak response accelerations at different locations of the bushing under the ground motion Sylmar EW-Up.

The graph shows that the system reduces the acceleration throughout the entire length of the bushing.

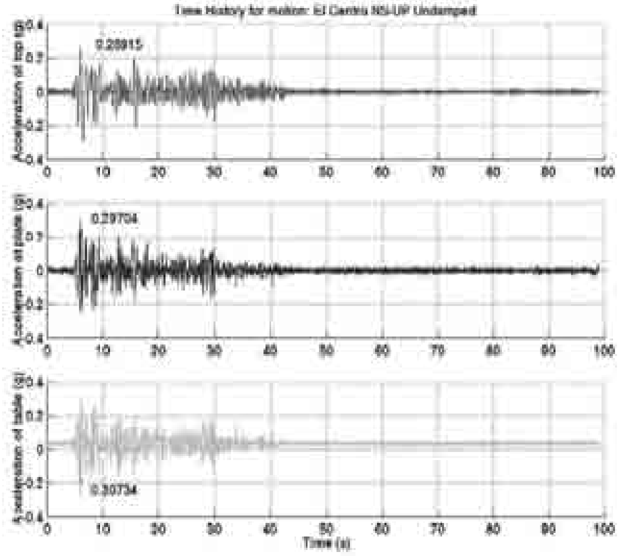


Figure 5: Time History for El Centro NS-Up with WEAR protection

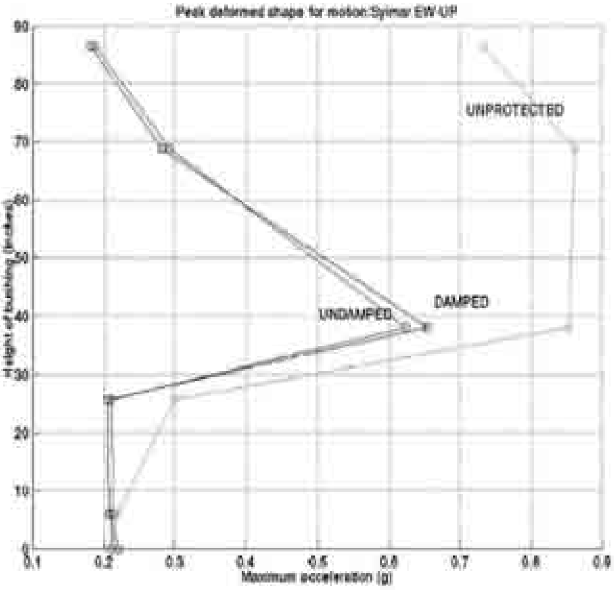


Figure 6: Peak response acceleration under Sylmar EW-Up

CONCLUSIONS

The WEAR isolation system was able to significantly reduced the peak tip acceleration of the bushing for all ground motions tested.

ACKNOWLEDGEMENTS

Principal investigator and/or faculty advisor: Professor Maria Feng. Acknowledgements: This project would not have been possible without the engineering expertise of Dr. Charles Hamilton. I also want to thank Enidine for providing the WEAR device and Edison International for donating the bushing.

HOW INFRARED THERMOGRAPHY HELPS SOUTHERN CALIFORNIA EDISON IMPROVE GRID RELIABILITY

Bob Turnbull and Steve McConnell, Southern California Edison, Alhambra, CA

ABSTRACT

The Infrared Thermography Inspection program at Southern California Edison has been fully integrated into their predictive maintenance protocol at all their facilities. This paper will provide an overview of the program.

Overviews of the physical facility structure and the staff organizational chart will be provided. Day-to-day inspection procedures, reporting mechanisms and follow-up protocol will be reviewed. Examples of critical findings and their repair disposition will be reviewed. Personnel training and certification programs will be discussed.

The paper will conclude with a review of the company's plans for marrying their infrared inspection program with currently planned facility expansion.

1. INTRODUCTION: A BRIEF OVERVIEW OF SOUTHERN CALIFORNIA EDISON

SoCal Edison services more than 4.1 million customers in a 50,000 square mile service territory in Southern California with a peak demand of 21GVA. Our 80 GVA installed capacity is delivered through 858 substations in which the equipment complement includes:

- 900 substation busses
- 3,300 power transformers
- 10,800 circuit breakers rated from 500 2,400 Volts

2. OVERVIEW OF THE SUBSTATION CONSTRUCTION AND MAINTENANCE DEPARTMENT

Figure 1 is a structural chart of our organization headed by Mr. Bob Turnbull, Technical Supervisor of Substation Construction and Maintenance Support Services. The heart of our controlled PdM program is the computer-based PassPort, which is the name for our Work Management System.

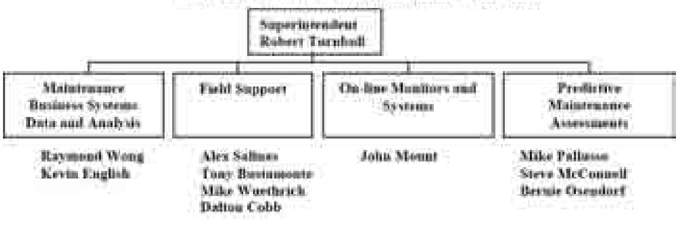


Figure 1. Our organization chart

Maintenance Business Systems data and analysis personnel provide:

- Substation Construction and Maintenance web-site technical lead and development
- PassPort Work Management System maintenance data
- Real-time KPI (key performance indicators) status
- Transporting and management of data
- Data communications systems architecture and database structure

Technical Field Support personnel provide:

- Installation, operation and maintenance recommendations, equipment failure analysis and reports and on-line oil filtering and Morgan Schaffer monitoring for transformers, reactors LTCs (load tap changers) and oil-filled CT/PTs (current transformers/voltage transformers).
- Installation, operation and maintenance recommendations for power circuit breakers and GIS (gas insulating systems).
- Maintenance cost factors provided by the equipment specification team member
- Capital replacement strategy provided by the transformer resource management team member
- Equipment problem resolution and supplier performance tracking by the ABB (Asea-Brown-Boveri) circuit breaker team member
- Resource manual, SF6 residual credit and new gas processing equipment provided by the SF-6 sulfur hexafluoride insulating gas) gas resources team member

On-line Monitoring personnel provide:

- On-line monitor links to our PassPort Work Management System
- Development of response time recorder replacement
- On-line equipment monitoring technical lead analysis and on-line monitor data

3. OUR PREDICTIVE MAINTENANCE ASSESSMENT PROGRAM

The mission of our PdM assessment (PMA) program is to improve and optimize grid reliability through the deployment of a multidisciplinary diagnostic program of equipment monitoring. The elements of this program are:

- PdM technical lead
- Maintenance initiatives
- Infrared diagnostics
- Acoustical diagnostics

- Vibration analysis
- Technical reporting
- Technical recommendations

With all these elements in place, and by means of our Predictive Maintenance Assessment (PMA) reports we have consistently demonstrated and documented failure avoidance and cost avoidance. Our Infrared Thermography Inspection program in particular has been most dramatic in this regard, as shall be demonstrated by examples given later in this paper. As a result we have convinced Management that our program should be ongoing and continuously expanded. This management "buy-in" is crucial to any program of this kind.

The importance of "selling" the program to our own team members as well as to Management cannot be emphasized enough. While Management's major concerns involve meeting business goals and maintaining profitability, the goals of our team members revolve more around job satisfaction, recognition of contribution by Management and personal enrichment and advancement. Working with one of the most modern and powerful technologies, such as infrared thermography, goes a long way toward achieving these goals. Nothing works like success, and we have been most successful in this area.

Field personnel also benefit by the success of the program. Frequent systematic inspections, meaningful findings and timely maintenance and repair optimize personnel and facility safety, minimize down time and enhance the job satisfaction of field operating personnel.

Most critical to our program is emphasizing the concept of a "team effort". Effective communications among team members is essential. The need to "close the loop" on any finding must remain foremost in the minds of all team members.

4. THE PMA PROCESS – CLOSING THE LOOP

The PMA process begins with regularly scheduled inspections at locations designated by the program managers and supplemented, on occasion, by special requests from the field. The technical specialists, such as the IR thermographers, perform the station inspections and determine the criticality of each finding, assigning a severity level to each detected abnormality. These levels, in the case of infrared thermography, are determined, for the most part, by the maximum detected temperature rise over a predetermined reference temperature, with Level 1 being the most critical and requiring the most immediate attention. The severity levels are defined as follows:

CRITICAL PROBLEM-PRIORITY LEVEL 1

Any problem that is identified as a safety hazard, or an immediate threat to grid reliability.

Identified through the use of diagnostic analysis and inspections.

ACTION REQUIRED: REPAIR IMMEDIATELY.

Foreman/electrician to make decision and take immediate corrective action to relieve the problem. Notify superintendent and program manager as soon as possible.

Note: the corrective action may be in the form of switching to relieve load, jumper out a disconnect switch, repair or remove equipment from service, etc.

SERIOUS PROBLEM-PRIORITY LEVEL 2

A problem that has the potential to develop into a hazardous condition and effect grid reliability. Identified through the use of diagnostic analysis and inspections.

ACTION REQUIRED: REPAIR IN THE IMMEDIATE FUTURE.

Foreman/technical specialist shall periodically monitor until repaired. Technical specialist notifies supervision and submits a written report. Foreman/program manager to establish priorities and schedule at monthly foremen's planning meeting.

Note: this type of problem will progressively worsen

INTERMEDIATE PROBLEM-PRIORITY LEVEL 3

A problem that is identified as no immediate threat to personnel or grid reliability.

Identified through the use of diagnostic analysis and inspections.

ACTION REQUIRED: SCHEDULE THE REPAIR.

Foreman / program manager to establish priorities and schedule at monthly foremen's planning meetings.

Note: this type of problem is less likely to be immediately detrimental to personnel or to the grid.

MINOR PROBLEM-PRIORITY LEVEL 4

A problem that is identified as requiring routine attention or maintenance. Little probability of physical damage. Identified through the use of diagnostic analysis and inspections.

ACTION REQUIRED: REPAIR AS PART OF REGULAR MAINTENANCE.

Foreman to establish priorities and complete repairs as time permits.

Note: this type of problem is very unlikely to be detrimental to personnel or to the grid.

The technical specialist then inputs the data into the WMS for the creation of field reports and maintenance repair work orders and the WMS generates the formal reports and work orders. The technical specialist also notifies the field maintenance crews directly when there are any severity Level 1 abnormalities detected.

Acting on the severity Level I abnormality report, the appropriate foreman generates and releases validation sheets directing repair crew (electricians) to perform the indicated repairs. The crew completes and documents the repairs, the site is reinspected and the foreman closes the work order and enters the repair data in the WMS.

All PMA findings are discussed during regularly scheduled monthly workload meetings attended by team personnel from all groups. Cost avoidance reports generated for all Level 1 abnormalities and repairs are discussed at these meetings.

Information for reporting trends to Management is derived by querying the WMS database. In this way reports are prepared from the PMA process for assuring continuing Management support.

1. EXAMPLES OF FINDINGS USING IR THERMOGRAPHY

We are currently using an Inframatrics model PM 295 uncooled-microbolometer based infrared camera. We employ three (3) Level II certified infrared thermographers. A fourth thermographer is currently in training.

We inspect a wide variety of operating equipment in our substations, including transformers, circuit breakers, bushings, disconnects, fuses, roto-switches, secondary current terminations, potheads, station batteries and relays. The following are illustrations of some of the abnormalities detected.

1. HOT BATTERY TERMINAL

A hot connection was detected on a battery terminal at our Anita Substation as illustrated in Figure 2. A rise of greater than 1°C is considered extraordinary in this type of equipment and required immediate attention.

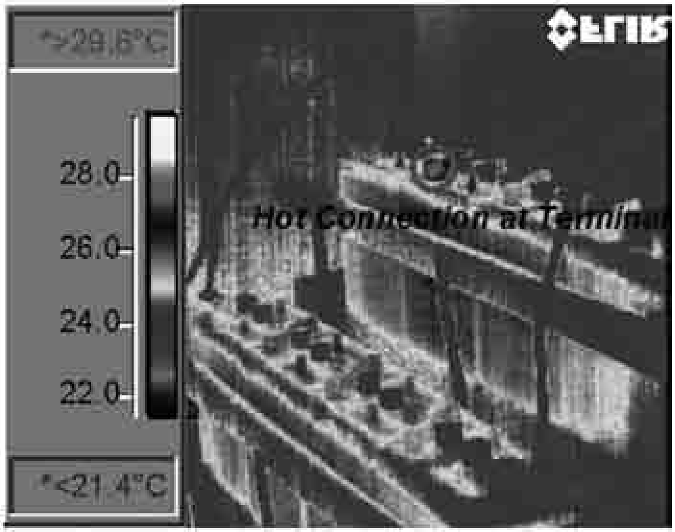


Figure 2 Hot connection at battery terminal (top)

2. OVERHEATED FAN CONTROL CIRCUIT TERMINALS

At our San Bernadino Substation, the 1AA bank fan control circuit exhibited 2 overheated terminals, as shown in the thermogram of Figure 3. The terminal at the left exhibited a rise of 135°C and the one at the right exhibited a rise of 153.6°C.

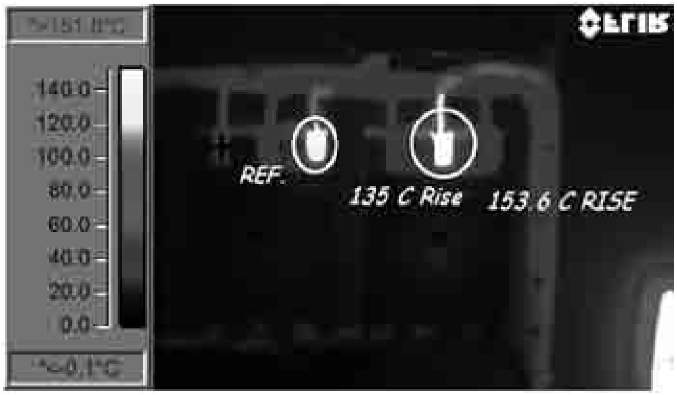


Figure 3. Fan bank control circuit with 2 overheated terminals

3. NO OIL FLOWING THROUGH TRANSFORMER RADIATOR

The thermogram of Figure 4., taken of a transformer bank at our Center Substation, illustrates the effect of the oil flow being shut off from the radiator at the right, resulting in a ΔT of greater than 20°C.

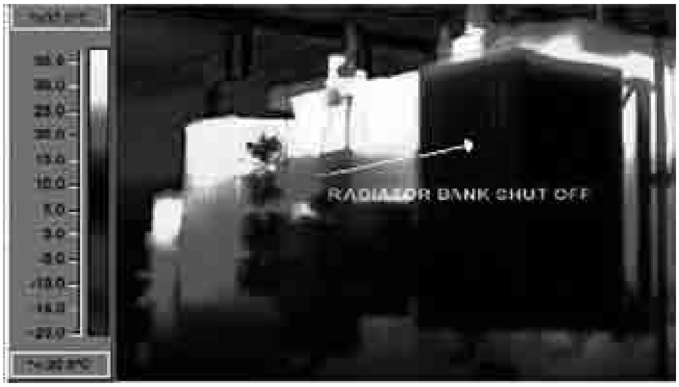


Figure 4. The effect of oil being shut off from the radiator at the right

4. OVERHEATED TAP CHANGER

The tap changer shown at the center of the thermogram of Figure 5, taken at our Elsinore Substation, was measured to be more than 7°C hotter than the main tank (shown at the left).

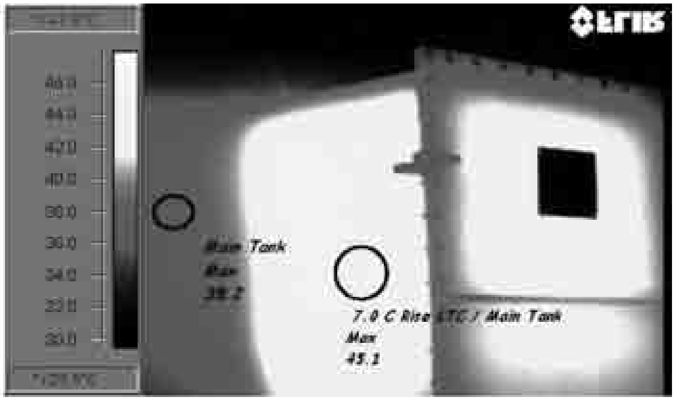


Figure 5. Tap changer (center) measured to be more than 7°C hotter than the main tank (left)

5. HOT BUSHING ROD

A hot bushing rod, detected at our Santiago Substation, Is shown in the thermogram of Figure 6. This bushing rod (lower center) had a measured temperature of 93.7°C, which was more than 60°C hotter than the reference point shown at the upper left.

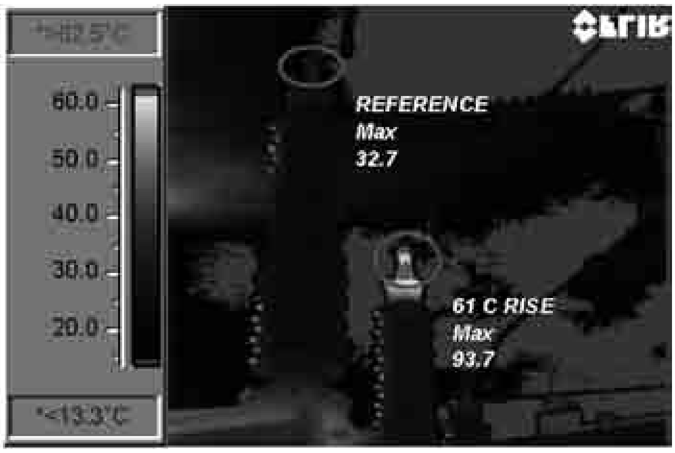


Figure 6. Hot bushing rod (center) measured to be more than 60°C hotter than reference bushing

6. LOW OIL LEVEL INDICATION

A measured temperature difference of greater than 10°C resulted from the low oil level in the radiator at the left of the thermogram of Figure 7, taken at our Sierra Madre Substation. The radiator at the right, with normal oil flow is at a measured temperature of 31.6°C compared to the 18.9°C reading taken on the left-hand bank.

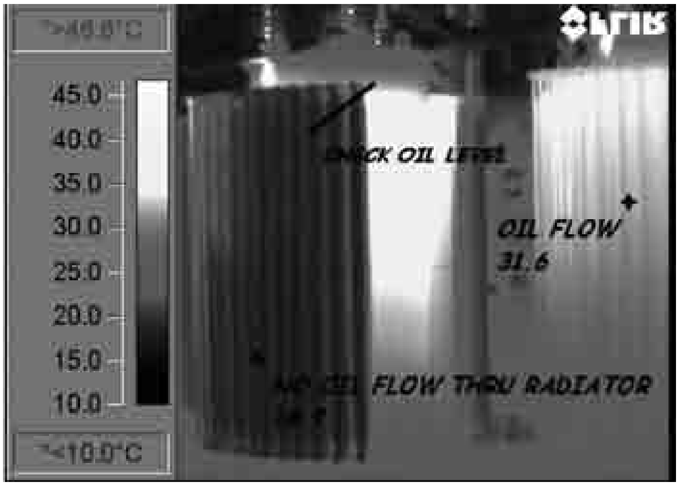


Figure 7. The low oil level in the left hand transformer bank results in no oil flow through the radiator

7. HOT FUSE CLIPS

Several hot fuse clips appeared on the thermogram of Figure 8., taken on the main DC fuse panel at our Anita Substation. As indicated in the thermogram, the clips marked from left to right exhibited ΔTs of 7.2°C, 4.6°C and 3.9°C respectively above the 28.0°C reference.

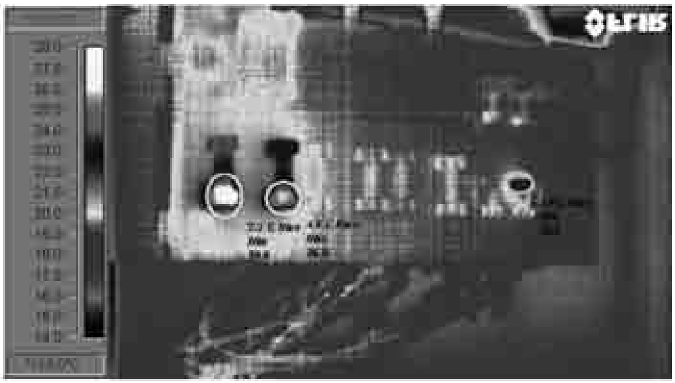


Figure 8. Hot fuse the clips exhibited ΔTs of 7.2°C, 4.6°C and 3.9°C respectively above the 28.0°C reference

2. SUMMARY: WHAT WE HAVE DONE TO DATE AND WHERE WE GO FROM HERE

1. COST AVOIDANCE BENEFITS

The “bottom line” in any PdM program resides in the cost avoidance results. From 1998 to the present we have inspected 450 substations with our multidisciplinary assessment program. Of the more than 3000 real anomalies detected and corrected over this period, more than 1500 (about 50%) were detected by means of infrared thermography. Table 2 illustrates the results by severity criteria over this testing period. Estimated savings in cost avoidance are in the millions of dollars per year from the IR thermography program alone, far exceeding the cost of the equipment and the training of our thermographers. Clearly, in terms of "bang for the buck", IR comes out way ahead.

Table 2. Anomalies detected from 1998 to the present in 450 substations inspected

Severity Level Classification	Total Anomalies Found	Total Anomalies Found by Infrared Thermography
Level I	299	159
Level II	1529	849
Level III	1449	503
Total	**3277**	**1508**

2. WHERE WE GO FROM HERE?

It has become apparent that the combination of incorporating infrared imaging cameras into our PMA, and meticulously training our personnel in their operation has paid off in terms of avoided down time, avoided repair costs and enhanced safety for our operating personnel and equipment.

Our company has planned extensive expansion of our substation network over the next few years, and our Management has come to recognize the impact of our Infrared Thermography Inspection program on safety and profitability. To keep pace with our planned expansion, we are projecting the addition of more thermal imaging systems and the training and assignment of another thermographer in the immediate future. Our future plans also call for training more field electricians to become infrared thermographers.

INFRARED DIAGNOSTICS ON PADMOUNT TRANSFORMER ELBOWS

Jeff Sullivan, Mississippi Power Company, Hattiesburg, MS

ABSTRACT

Mississippi Power Company has been a leader and trendsetter in finding new and better ways to increase customer satisfaction. For this reason, we implemented a program of infrared thermographic inspection using infrared thermal imaging cameras, of all the electrical equipment in our facilities, including all of our 750 KVA to 2500 KVA padmount transformers, one of which had failed disastrously.

During a survey of these transformers, I detected thermal problems with more than 30% of the 400 scanned, all associated with the high side elbow connection. Further investigation related the failure mechanisms to improper installation techniques during both the original installation and the routine preventive-maintenance replacement of the elbows.

Using newer improved equipment and holding training classes on proper installation and removal of this equipment, we reduced the occurrence rate of these anomalies from 30% to less than 2%. Our management authorized the purchase of an additional infrared camera, also known as a thermal imaging camera.

This paper describes the program and the findings, explains the diagnostics and illustrates the contrast between properly and improperly installed equipment.

1. INTRODUCTION

Mississippi Power Company began doing infrared scans, using an infrared thermal imaging camera in 1994, as a support service to our industrial and commercial customers. Over the past several years, we have come to realize the value of using infrared thermal imaging cameras to find and solve problems for our customers as well as for ourselves. Being proactive, our department added more people to keep up with the increased needs of our customers and to provide the best reliable service to our customers. We did this by purchasing additional infrared thermal imaging cameras and increasing the scope of work to include infrared scans of our substations, feeders and all of our padmount transformers rated from 750KVA up to 2500KVA. We now have three infrared thermal imaging cameras in Mississippi Power Company.

Padmount transformers are transformers that are sealed in metal containers and filled with oil. They are used to step up or down the output voltages depending on customer needs. They range in size form 50KVA to 2500KVA and vary in shape. The main reason for using padmount transformers is that they offer a wide selection of load capacity in modular, encapsulated form. Other reasons include esthetics and safety; in designated areas such as in subdivisions, encapsulated padmount transformers are safer to operate and can be placed underground, where they are out of sight and impervious to falling trees and other hazards.

The elbow problems that we found and identified with the use of the Infrared camera were put into three categories for the purpose of identifying, tracking and repairing the problems. They are contact, probe and crimp problems. With the use of the infrared camera and through training we have reduced the problems from 30% to less than 2%.

2. CLASSIFICATION OF PROBLEMS

My job consists of doing infrared scans for customers, on padmount transformers and on our feeders. Since additional personnel were assigned to the department, I have been able to concentrate on padmount transformers more than was possible in the past. I have used this opportunity to track and record the data from my findings. As it turned out, I discovered that we have a serious ongoing problem with padmount transformer elbows. With 400 transformers scanned, I found that 30% of the padmount transformers had an elbow problem. With experience gained from working in electrical substations for 12 years as an electrician, and from other sources, I was able to determine what caused the problems and how to correct them. After reviewing them, I classified them into three categories, contacts, probes and crimps.

The first category is the contact problem. This occurs when the female bushing is replaced after a failure. If grease is applied incorrectly on the stud of the internal winding of the transformer, when the female bushing is threaded onto the stud, it forces the grease into the contacts of the female bushing. When the transformer is energized, the grease heats up, turning into a liquid and acting like a hydraulic pump, forcing the probe backwards. This action causes the contacts to arc and eventually burn up. Similar heating will occur if the elbow is not properly seated when installed. Fig. 1 illustrates two examples of an elbow that is not properly seated due to a mechanical error or grease being applied improperly.

The second problem category is the loose probe; related to the method of removing the elbow from the transformer after the unit had been in service. When an elbow has been installed for a period of time, it creates a vacuum or suction due to the load of the transformer. To remove the elbow from the transformer, it has to be twisted back and forth several times to break the vacuum or suction it had created due to load changes. Each time the elbow is twisted counterclockwise, it causes the probe to loosen from the threaded crimp and eventually causes the probe to burn up. Through proper training and the use of a ring stick with a slide weight on it, the elbows could be removed by one person and installed properly, therefore practically eliminating this problem. Fig. 2 illustrates two examples of loose probes.

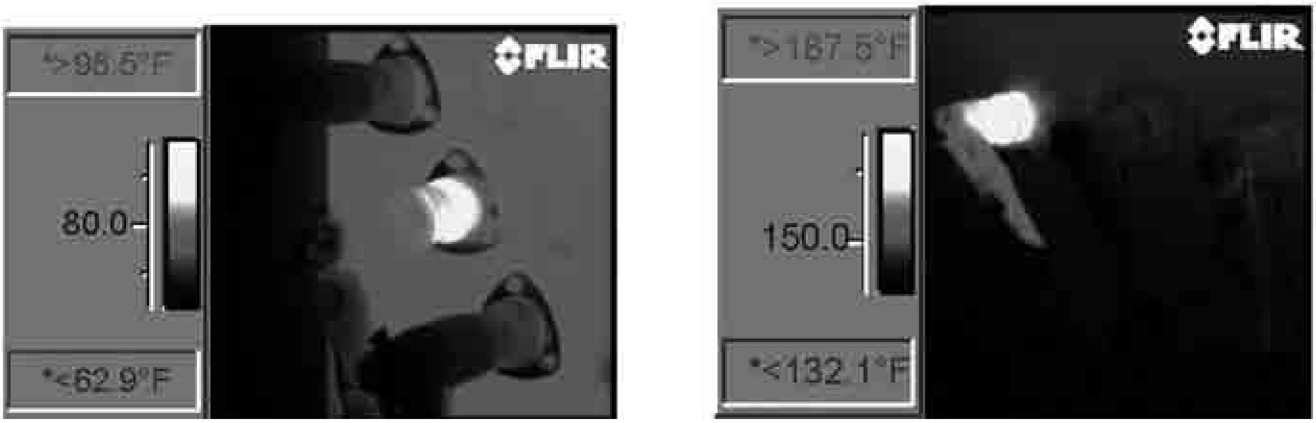


Figure 1. Two examples of heating on a padmount transformer due to improper elbow installation that will lead to contact damage

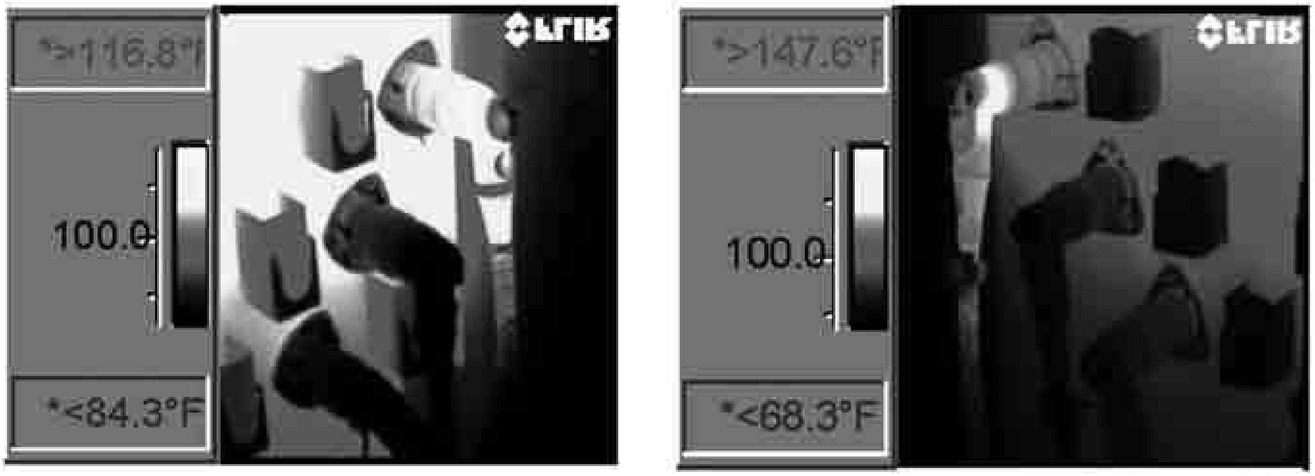


Figure 2. Two examples of heating on a padmount transformer due to loose probes

The third problem category concerns the crimp on the underground dip wire. There are two different problems associated with the crimp. The first occurs when the wrong size crimp is used. The second occurs as a result of an improperly executed crimp connection. Either one will cause overheating that will lead to a failure. Fig. 3 is an example of the result of a bad crimp connection.

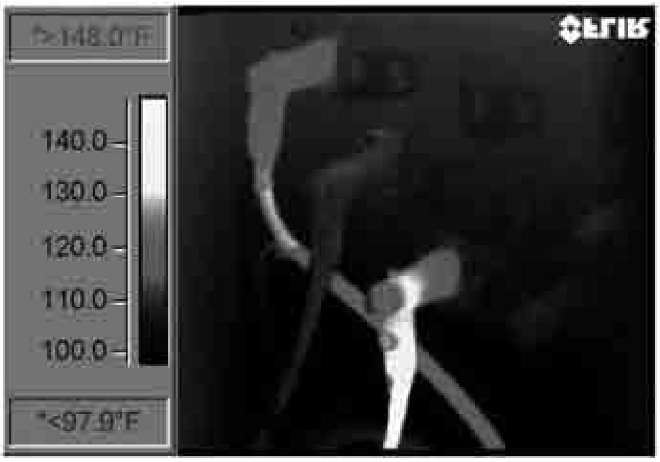


Figure 3. Overheating of an elbow caused by a bad crimp connection

3. CONCLUSIONS AND COST AVOIDANCE SUMMARY

Through the use of the infrared camera, we have found and solved problems that would have been disastrous if they had not been detected in time. One of the best results of doing infrared scans is that it has allowed Mississippi Power Company to greatly improve customer relations in dependability and reliability. Unscheduled outages are a big problem to a company like ours, and by using the infrared camera in routine predictive maintenance we perform, we have greatly reduced our customers' outages.

If a padmount transformer elbow were to fail for one of our larger customers, the average time to get the customer back to 100% production would be about four hours of outage time. Several of our customers estimate their losses to be about $1,000 a minute when they are out of power due to an elbow failure problem. This computes to a $240,000 customer loss for an outage.

By using the infrared camera to find the problems, identify and fix the problems on a controlled outage situation, Mississippi Power Company and our customers have shared in the rewards. The elbow problems found on padmount transformers were found, identified and fixed, reducing the problem by 28% through proper training of everyone involved with installation and removal of padmount transformer elbows. This saved Mississippi Power Company from loss of revenue, having to pay overtime and from destruction of expensive equipment, thereby improving customer relations and satisfaction. Also, the customer benefited greatly from Mississippi Power Company being proactive by offering infrared services to them. The bottom line is that the infrared camera is a win/win for everyone. It is one of the best purchases a company can make. Not having an Infrared camera in our business would be like going back into the Stone Age.

TRANSFORMER RATINGS

Courtesy: Teal Electronics

Transformer size or capacity is most often expressed in kVA. "We require 30 kVA of power for this system" is one example, or "The facility has a 480 VAC feed rated for 112.5 kVA".

However, reliance upon only kVA rating can result in safety and performance problems when sizing transformers to feed modern electronic equipment. Use of off-the-shelf, general purpose transformers for electronics loads can lead to power quality and siting problems:

- Single phase electronic loads can cause excessive transformer heating.
- Electronic loads draw non-linear currents, resulting in low voltage and output voltage distortion.
- Over sizing for impedance and thermal performance can result in a transformer with a significantly larger footprint.

It is vital for the systems designer to understand all of the factors that affect transformer effectiveness and performance.

THERMAL PERFORMANCE

Historically, transformers have been developed to supply 60 Hz, linear loads such as lights, motors, and heaters. Electronic loads were a small part of the total connected load. A system designer could be assured that if transformer voltage and current ratings were not exceeded, the transformer would not overheat, and would perform as expected.

A standard transformer is designed and specified with three main parameters: kVA Rating, Impedance, and Temperature Rise.

KVA RATING

The transformer voltage and current specification. KVA is simply the load voltage times the load current. A single phase transformer rated for 120 VAC and 20 Amperes would be rated for 120 x 20 = 2400 VA, or 2.4 KVA (thousand VA).

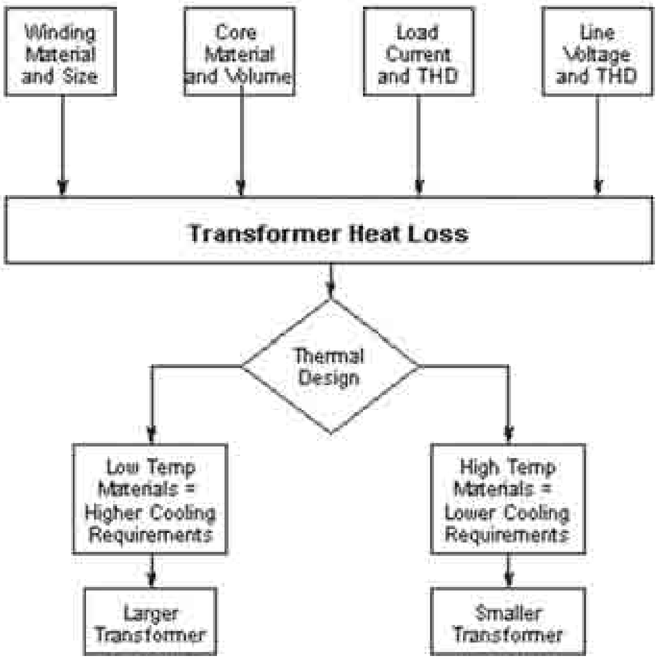
IMPEDANCE

Transformer Impedance and Voltage Regulation are closely related: a measure of the transformer voltage drop when supplying full load current. A transformer with a nominal output voltage of 120 VAC and a Voltage Regulation of 5% has an output voltage of 120 VAC at no-load and (120 VAC - 5%) at full load - the transformer output voltage will be 114 VAC at full load.

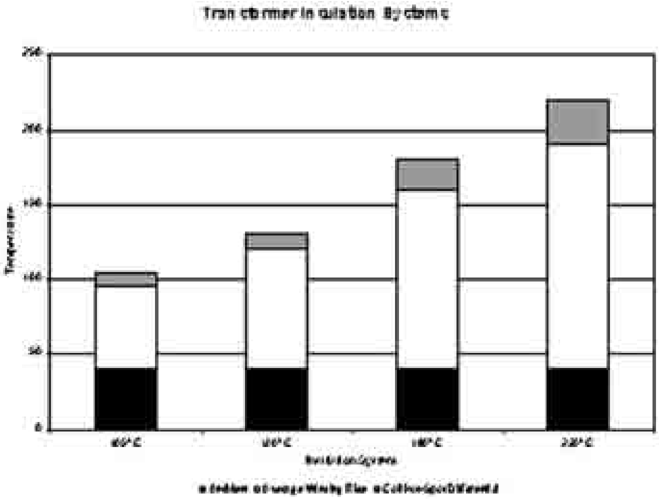
Impedance is related to the transformer thermal performance because any voltage drop in the transformer is converted to heat in the windings.

TEMPERATURE RISE

Steel selection, winding capacity, impedance, leakage current, overall steel and winding design contribute to total transformer heat loss. The transformer heat loss causes the transformer temperature to rise. Manufacturers design the transformer cooling, and select materials, to accommodate this temperature rise.



Use of less expensive material with a lower temperature rating will require the manufacturer to design the transformer for higher airflow and cooling, often resulting in a larger transformer. Use of higher quality materials with a higher temperature rating permits a more compact transformer design.



"K" FACTOR TRANSFORMER RATING

In the 1980s, power quality engineers began encountering a new phenomenon: non-linear loads, such as computers and peripherals, began to exceed linear loads on some distribution panels. This resulted in large harmonic currents being drawn, causing excessive transformer heating due to eddy-current losses, skin effect, and core flux density increases.

Standard transformers, not designed for nonlinear harmonic currents, were overheating and failing even though RMS currents were well within transformer ratings.

In response to this problem, IEEE C57.110-1986 developed a method of quantifying harmonic currents. A "k" factor was the result, calculated from the individual harmonic components and the effective heating such a harmonic would cause in a transformer. Transformer manufacturers began designing transformers that could supply harmonic currents, rated with a "k" factor. Typical "K" factor applications include:

K-4: Electric discharge lighting, UPS with input filtering, Programmable logic controllers and solid state controls

K-13: Telecommunications equipment, UPS systems, multi-wire receptacle circuits in schools, health-care, and production areas

K-20: Main-frame computer loads, solid state motor drives, critical care areas of hospitals

"K" factor is a good way to assure that transformers will not overheat and fail. However, "K" factor is primarily concerned with thermal issues. Selection of a "K" factor transformer may result in power quality improvement, but this depends upon manufacturer and design.

TRANSFORMER IMPEDANCE

Transformer impedance is the best measure of the transformer's ability to supply an electronic load with optimum power quality. Many power problems do not come from the utility but are internally generated from the current requirements of other loads.

While a "K" factor transformer can feed these loads and not overheat, a low impedance transformer will provide the best quality power. As an example, consider a 5% impedance transformer. When an electronic load with a 200% inrush current is turned on, voltage sag of 10% will result. A low impedance transformer (1%) would provide only 2% voltage sag - a substantial improvement.

Transformer impedance may be specified as a percentage, or alternately, in Ohms (W) from Phase-Phase or Phase-Neutral.

HIGH FREQUENCY TRANSFORMER IMPEDANCE

Most transformer impedance discussions involve the 60 Hz transformer impedance. This is the power frequency, and is the main concern for voltage drops, fault calculations, and power delivery. However, non-linear loads draw current at higher harmonics. Voltage drops occur at both 60 Hz and higher frequencies.

It is common to model transformer impedance as a resistor, often expressed in ohms. In fact, a transformer behaves more like a series resistor and inductor. The voltage drop of the resistive portion is independent of frequency; the voltage drop of the inductor is frequency dependent.

Standard Transformer impedances rise rapidly with frequency. However, devices designed specifically for use with non-linear loads use special winding and steel lamination designs to minimize impedance at both 60 Hz and higher frequencies. As a result, the output voltage of such designs is far better quality than for standard transformers

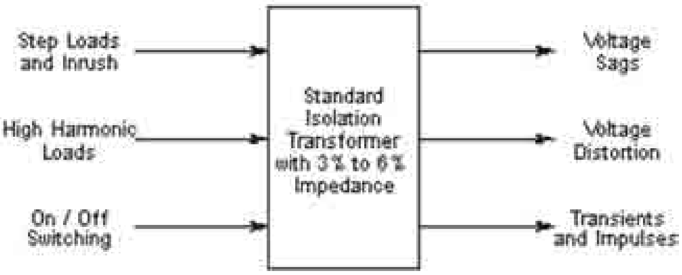
RECOMMENDATIONS FOR TRANSFORMER SIZING

System design engineers who must specify and apply transformers have several options when selecting transformers.

DO IT YOURSELF APPROACH

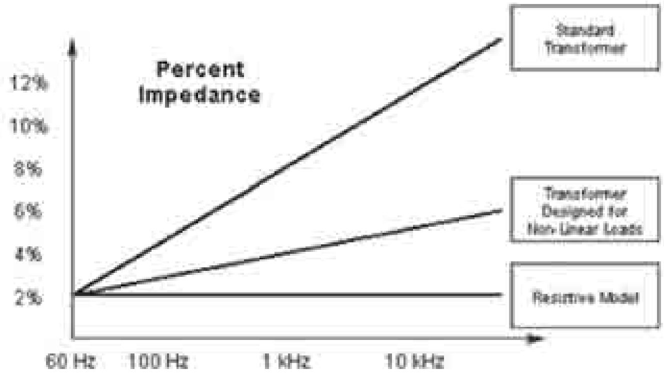
With this approach, a larger than required standard transformer is specified in order to supply harmonic currents and minimize voltage drop. Transformer over-sizing was considered prudent design in the days before transformer manufacturers understood harmonic loads, and remains an attractive option from a pure cost standpoint. However, such a practice today has several problems:

- A larger footprint and volume than low impedance devices specifically designed for non-linear loads
- Poor high frequency impedance
- Future loads may lead to thermal and power quality problems



"K"-FACTOR RATED TRANSFORMERS

Selecting and using "K"-factor rated transformers is a prudent way to ensure that transformer overheating will not occur. Unfortunately, lack of standardization makes the "K" factor rating a measure only of thermal performance, not impedance or power quality.



Some manufacturers achieve a good "K" factor using design techniques that lower impedance and enhance power quality, others simply de-rate components and temperature ratings. Only experience with a particular transformer manufacturer can determine if a "K" factor transformer addresses both thermal and power quality concerns.

TRANSFORMERS DESIGNED FOR NON-LINEAR LOADS

Transformers designed specifically for non-linear loads incorporate substantial design improvements that address both thermal and power quality concerns. Such devices are low impedance, compact, and have better high frequency performance than standard or "K" factor designs. As a result, this type of transformer is the optimum design solution.

This type of transformer may be more expensive than standard transformers, due to higher amounts of iron and copper, higher quality materials, and more expensive winding and stacking techniques. However, the benefits of such a design in power quality and smaller size justify the extra cost and make the low impedance transformer the most cost effective design overall.

HARMONICS SELECTION AND RATING OF TRANSFORMERS

By: Prof Jan Desmet, Hogeschool West-Vlaanderen
And
Gregory Delaere, Labo Lemcko

Courtesy: Leonardo Power Quality Initiative (LPQI)

SELECTION AND RATING OF TRANSFORMERS INTRODUCTION

The number of non-linear loads which draw non-sinusoidal currents even if fed with sinusoidal voltage connected to the power supply system is large and is continuing to grow rapidly. These currents can be defined in terms of a fundamental component and harmonic components of higher order. In power transformers, the main consequence of harmonic currents is an increase in losses, mainly in windings, because of the deformation of the leakage fields.

Higher losses mean that more heat is generated in the transformer so that the operating temperature increases, leading to deterioration of the insulation and a potential reduction in lifetime. As a result, it is necessary to reduce the maximum power load on the transformer, a practice referred to as de-rating, or to take extra care in the design of the transformer to reduce these losses.

To estimate the de-rating of the transformer, the load's K-factor may be used. This factor is calculated according to the harmonic spectrum of the load current and is an indication of the additional eddy current load losses. It reflects the excess losses experienced in a traditional wire wound transformer. Modern transformers use alternative winding designs such as foil windings or mixed wire/foil windings. For these transformers, the standardized K-factor – derived for the load current - does not reflect the additional load losses and the actual increase in losses proves to be very dependent on the construction method. It is therefore necessary to minimize the additional losses at the design stage of the transformer for the given load data using field simulation methods or measuring techniques.

TRANSFORMER LOSSES

Transformer losses consists of no-load (or core loss) and load losses. This can be expressed by the equation below.

PT = PC + PLL (1)

Where: PC = core or no-load loss
PLL = load loss PT = total loss.

Core or no-load loss is due to the voltage excitation of the core. Although the magnetizing current does include harmonics, these are extremely small compared with the load current and their effect on the losses is minimal. As a result, it is assumed in standards such as ANSI/IEEE C57.110 that the presence of harmonics does not increase the core loss.

Load losses are made up of I_ R loss, eddy current loss and stray loss, or in equation form:

PLL = I2R + PEC + PSL (2)

Where: I_R = loss due to load current and DC resistance of the windings
PEC = winding eddy current loss
PSL = stray losses in clamps, tanks, etc.

The I_R loss is due to the current flowing in the resistance of the windings. It is also called ohmic loss [1] or dc ohmic loss [2]. The ohmic loss is proportional to the square of the magnitude of the load current, including the harmonic components, but is independent of the frequency. It is determined by measuring the DC resistance and calculating the resulting loss using the winding currents at full load. There are no test methods available to determine individual winding eddy current loss or to separate transformer stray loss from eddy current loss. Instead, the total stray and eddy current loss is determined by determining the total load loss and subtracting the calculated ohmic losses, i.e.,

PLL - I2R = PEC + PSL (3)

The eddy current loss is assumed to vary with the square of the rms current and the square of the frequency (harmonic order h), i.e.

$$P_{EC} = P_{EC,R} \sum_{h=1}^{h=h_{max}} \left[\frac{I_h}{I_R} \right]^2 h^2 \qquad (4)$$

1,2,3, etc. = the greatest harmonic order to be considered hmax
I_h = current at harmonic order h, amperes
I_R = rated current, amperes
$P_{EC,R}$ = eddy current loss at rated current and frequency.

The eddy current loss depends on the square of the conductor dimension perpendicular to the leakage flux field. At the ends of the winding, the flux field bends and the larger dimension of the rectangular conductor is perpendicular to a vector component of the leakage flux field. Equalizing the height of die primary and secondary windings, which can be achieved with any winding design, reduces the concentrated eddy loss at the winding ends. However, the magnitude is still greater than the middle of the winding due to this bending of the leakage flux field. Reducing conductor size reduces the percentage eddy current loss but, increases the ohmic loss. Using multiple strands per winding reduces both eddy current loss and ohmic loss, but because the conductors are of unequal length, circulating currents are generated which cause excess loss. This can be avoided by the use of continuously transposed conductors, shown in Figure 1, for the high current winding. Small transformers inherently have small conductor sizes due to low currents.

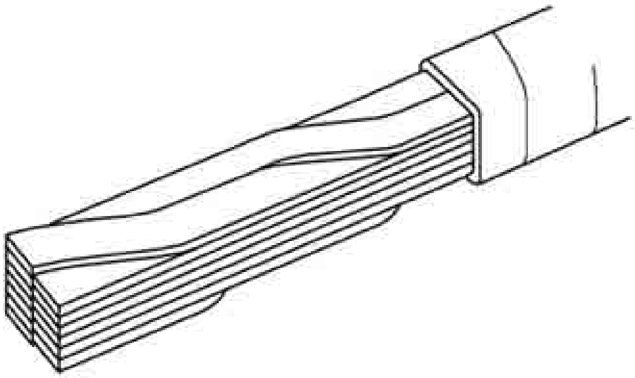


Figure 1 – Continuously transposed conductor

Stray loss occurs due to the stray flux which introduces losses in the core, clamps, tank and other iron parts. Stray loss may raise the temperatures of the structural parts of the transformer. For dry-type transformers, increased temperatures in these regions do not contribute to an increase in the winding hot-spot temperature. For liquid-immersed transformers, the stray loss increases the oil temperature and thus the hot-spot temperature of the windings. Stray losses are difficult to calculate and it is common to assume that the losses will vary as the square of the current times the frequency (harmonic order), as shown by:

$$P_{SL} = P_{SL,R} \sum_{h=1}^{h=h_{max}} \left[\frac{I_h}{I_R} \right]^2 h \qquad (5)$$

THE ‘K-FACTOR’

There are different approaches to accounting for additional losses in selecting a transformer. The first, devised by transformer manufacturers in conjunction with Underwriters Laboratories in the United States, is to calculate the factor

$$K = \sum_{h=2\square}^{h=h_{max}} h^2 I_h^2 \qquad (6)$$

increase in eddy current loss and specify a transformer designed to cope; this is known as the ‘K-factor’.

Ih = the fraction of total rms load current at harmonic number h

Many power quality meters read the K-factor of the load current directly. Once the K-factor of the load is known, it is a simple matter to specify a transformer with a higher K-rating from the standard range of 4, 9, 13, 20, 30, 40, 50.

Note that a pure linear load – one that draws a sinusoidal current – would have a K-factor of unity. A higher K-factor indicates that the eddy current loss in the transformer will be K times the value at the fundamental frequency. ‘K-rated’ transformers are, therefore, designed to have very low eddy current loss at fundamental frequency.

THE ‘FACTOR K’

The second method, used in Europe, is to estimate by how much a standard transformer should be de-rated so that the total loss on harmonic load does not exceed the fundamental design loss; this is known as ‘factor K’.

$$K = \left[1 + \frac{e}{1+e} \left(\frac{I_1}{I} \right)^2 \sum_{h=2}^{h_{max}} \left(h^q \left(\frac{I_h}{I_1} \right)^2 \right) \right]^{\frac{1}{2}} \qquad (7)$$

where:

e = ratio of fundamental frequency eddy current loss to ohmic loss, both at reference temperature

h = harmonic number I= rms of the sinusoidal current including all harmonics

I_h = magnitude of the hth harmonic

I_1 = magnitude of the fundamental current

Q = an exponential constant that is dependent on the type of winding and frequency. Typical values are 1.7 for transformers with round or rectangular cross-section conductors in both windings and 1.5 for those with foil low-voltage windings.

THE ADDITIONAL LOSS FACTOR

$$K_{\Delta R}(f) = \frac{R_{AC}(f) - R_{DC}}{R_{AC}(f_1) - R_{DC}} \qquad (8)$$

The third method is called additional loss factor. A resistance factor is defined as follows:

where:

R_{DC} = the equivalent series DC-resistance

R_{AC} = the series AC-resistance.

R_{AC} is frequency dependent, due partly to current redistribution in the winding, and is determined for each harmonic frequency. The type of construction and the placement of the windings have a major effect on the shape of the relationship between R_{AC} and frequency. Finally, the total additional loss factor ‘$K_{\Delta P}$’ is determined as the sum of the frequency dependent losses at each frequency arising from the R_{AC}. This requires knowledge of the harmonic current spectrum of the load.

$$K_{\Delta P} = \sum_{f>f_1} K_{\Delta R}(f) \left(\frac{I_f}{I_R} \right)^2 \qquad (9)$$

Where: $K_{\Delta P}$= additional loss factor $K_{\Delta P}$= resistance factor

I_f = current at harmonic frequency f

I_R = rated current.

To determine this factor for a given transformer, prototype or computation model, the series resistances or short circuit resistances have to be determined, either by measurement or by simulation.

EXPERIMENTAL TESTS ADDITIONAL LOSSES IN PRESENCE OF CURRENT HARMONICS

If the harmonic spectrum is known, or can be measured or predicted, the additional losses can be easily calculated. In principle, the process of calculation is as follows:

- Determine all the components of additional losses due to the presence of harmonics
- Determine the harmonic spectrum, either by measurement or by estimation, taking account of all harmonic generating equipment – especially electronic converters
- Calculate the contribution of each harmonic and determine the total additional loss.

In practice, it is important to use the real harmonic current magnitudes rather than theoretical values. Table 1 shows the calculated additional losses, for harmonic currents up to order 25, for two transformers at normal environmental temperature, assuming the current harmonic spectrum to be that illustrated as the theoretical values in Figure 2. The results demonstrate that the transformer characteristics play an important role in determining the losses with harmonic loads. The transformers in this example were measured at slightly different temperatures (21.5°C for the first and 22.8°C for the second); this will not change the character of the result.

Loss type	First Transformer (21.5°C)	Second Transformer (22.8°C)
Additional with sinusoidal current	520 W	1721 W
Additional with non-sinusoidal current	871 W	4351 W

Table 1 – Additional losses calculated in presence of non-sinusoidal currents

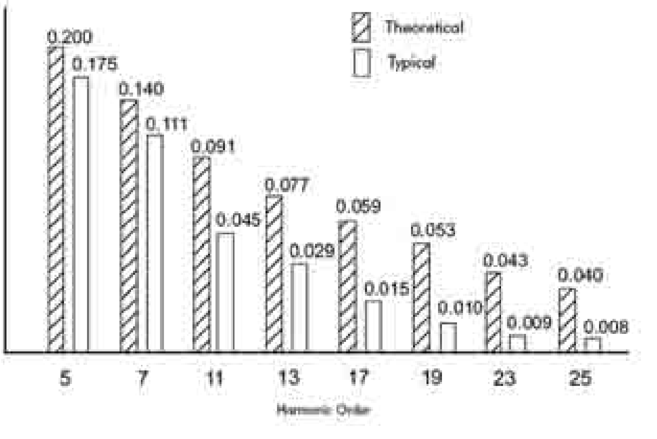


Figure 2 – Theoretical and real values of current harmonics for a six pulse converter

CALCULATION OF THE K-FACTOR

Table 2 shows the calculation of the K-factor for the harmonic theoretical spectrum of Figure 2 on a per unit basis.

The first step is to calculate the rms value of total current I, 1.0410 in this case, after which the squares of the proportionate values of each harmonic current can be calculated, leading to the value of K. For such a load, a transformer with a K rating of 9 would be appropriate for a six-pulse converter.

Harmonic No	I_h/I_1	$(I_h/I_1)^2$	I_h/I	$(I_h/I)^2$	$(I_h/I)^2 \times h^2$
1	1.000	1.0000	0.9606	0.9227	0.9227
5	0.200	0.0400	0.1921	0.0369	0.0227
7	0.140	0.0196	01345	0.0181	0.8862
11	0.091	0.0083	0.0874	0.0076	0.9246
13	0.077	0.0059	0.0740	0.0055	0.9420
17	0.058	0.0034	0.0557	0.0031	0.8971
19	0.056	0.0031	0.0538	0.0029	1.0446
23	0.043	0.0018	0.0413	0.0017	0.9025
25	0.040	0.0016	0.0384	0.0015	0.0227
	Sum =	1.0838			8.3476
	Total (rms) =	1.0410			
				K-factor =	8.3476

Table 2 - Calculation of the K-factor

CALCULATION OF THE FACTOR K

The first step in establishing factor K (Table 3) is to discover the value of e, the ratio of eddy current loss to total load loss at fundamental frequency. The transformer manufacturer should be able to provide this; otherwise it is likely to lie in the range of 0.05 to 0.1. The exponent q depends critically on the construction of the transformer and should also be available from the manufacturer. Q is likely to lie in the range 1.5 to

1.7. As before, the calculations are based on the theoretical values from Figure 2.

In practice, the transformer would need to be de-rated to 84.75% (1/1.18) of nominal power rating when supplying a six-pulse converter.

Harmonic No	I_h/I_1	$(I_h/I_1)^2$	h	$(I_h/I_1)^2 \times h$
1	1.000	1.0000	1.0000	1.0000
5	0.200	0.0400	15.4258	0.6170
7	0.140	0.0196	27.3317	0.5357
11	0.091	0.0083	58.5842	0.4880
13	0.077	0.0059	78.2895	0.4642
17	0.058	0.0034	123.5274	0.4155
19	0.056	0.0031	149.2386	0.4680
23	0.043	0.0018	206.5082	0.3818
25	0.040	0.0016	237.9567	0.3807
	Sum =	1.0838	$\lvert\alpha\rvert$ =	4.7511
	Total (rms) =	1.0410	$\lvert\alpha\rvert \times (I_1/I)^2$ =	4.3839
			e/(e+1)	0.091
	$(I_1/I)^2$ =	0.9227		
			K^2 =	1.3885
			K =	1.18

Table 3 - Calculation of the Factor K

TRANSFORMER DESIGN CONSIDERATION

INTRODUCTION

Many transformer manufacturers have developed designs rated for non-sinusoidal load currents while optimizing their production costs. The design process involves an analysis of the eddy current loss distribution in the windings and calculation of the hot spot temperature rise. Eddy current losses due to the leakage flux distribution are concentrated in the ends of the winding. Analysis of the eddy loss distribution may be performed using finite element or other type computer programs. Specialized software programs are commercially available.

For larger transformers, above about 300 kVA, a combination of testing and analysis may be the only economically practical approach. Thermal studies should be conducted using embedded thermocouples installed in test windings of prototype transformers to measure hot spot temperature to refine mathematical models to calculate the hot spot temperature.

ELECTROMAGNETIC ANALYSIS

The subject of harmonics has received much publicity in recent times leading to the belief that the industry is only just beginning to understand the effect of harmonics and to calculate the increased eddy current losses. In fact, the study of the effects is quite old, with eddy current losses in conductors in a magnetic field dating from 1906. Many early investigations were highly mathematical and the flux plots given in these early papers were every bit as detailed, and probably as accurate, as those produced by modern computer programs.

With the availability of computers, methods were developed to compute electrical fields and eddy current losses in transformers. Many commercial computer programs are currently available and a list is given in the 1989 IEEE Spectrum article by Cendes [5]. These computer programs produce elegant plots; however their accuracy cannot be proven.

THERMAL ANALYSIS

Although hot spot temperature is an important performance parameter to be met by the manufacturer, there are currently no defined test methods, nor is there a requirement that this parameter be measured on production or prototype transformers. This is important since temperature is fundamental in determining the life of the equipment.

The hot spot temperature in dry-type transformers is sometimes a contentious issue. Hot spots, the positions of the highest temperature, occur naturally due to the non-uniform heat generation and the fact that the rate of heat transfer to the environment is not uniform; dry-type transformers have unique heat-transfer characteristics that are not well understood. Most manufacturers of dry-type transformers simply add 30 deg C to the average temperature rise (calculated using empirical equations) and claim this is according to standards. In fact, IEEE Standard C57.12.01- 1989 requires that both average winding temperature rise and hot spot temperature are limits to be met at rated kVA. The difference between these two limits happens to be 30 deg C but the use of 30 deg C as a ‘rule of thumb’ was not intended.

CONCLUSION

Non-sinusoidal currents cause excessive heating in transformers due to the increase in the losses, especially the eddy current losses. Where existing or standard transformers are used to supply non-linear loads, they should be de-rated in a manner appropriate to their construction. For new installations, specially constructed (or K rated) transformers should be selected if possible, otherwise appropriate de-rating should be used.

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A NEW TECHNIQUE FOR ON-LINE MONITORING OF TRANSFORMER BUSHINGS

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Abstract: Bushings are essential components of power transformers and are one of the common causes of catastrophic failure for transformers. The majority of bushings are as old as the transformers and therefore maintaining and monitoring of bushing condition is essential. The power factor and capacitance (PF&C) are the best indicators of the bushing's condition. Off-line measurement of the PF&C needs to remove the power transformer from the network and a normal capacitance (NC) must be installed in the substation. In this paper a novel method for on-line measuring of PF&C for power transformer condenser bushings with the software, hardware and sensors used in this method are introduced. According to laboratory measurement results, this method can be used with acceptable accuracy in measurement of PF&C to detect a change in the bushing oil level, an increase in the oil moisture of the bushing and the temperature variation of the bushing oil.

1 INTRODUCTION

Power transformers belong to the most expensive and strategic components of any power system. Insulation breakdown as a serious failure of a large power transformer can generate substantial costs for repair and financial losses due to power outage. Therefore, utilities have incentive to assess the condition of their transformers, in particular the condition of the high-voltage insulation system, with the aim to minimize the risk of failures and to avoid forced outages of strategically important units. Condition monitoring and assessing of the insulation quality in large power transformers is an area of work currently being pursued by many laboratories and utilities. Power factor and capacitance measurement are accepted techniques for the investigation of the dielectric properties of high-voltage insulation materials. The famous method for measuring the PF&C is Schering Bridge. Measurements of PF&C by Schering Bridge need to remove the power transformer from the network (off-line) and a NC must be installed which can usually not be done periodically (monthly or weekly). On the other hand, off-line testing on transformer bushings is performed at 10kV and the standard off-line test is far less sensitive to impending failures. In inclement weather or at time with high humidity, maintenance crews at utilities will not perform power factor tests due to their concerns about inaccurate readings. It is, therefore, important that bushings be checked more frequently at rated voltage and operating temperature, especially for those transformers that have a history of high failure rates.

2 POWER TRANSFORMER BUSHINGS

High-voltage bushings for use in transformers and breakers are made by several principal types, as composite, compound-filled, dry, condenser, oil-filled, oil-immersed, oil-impregnated paper-insulated, resin-bonded and solid (ceramic) bushing. Operating records show that about 90 percent of all preventable bushing failures are caused by moisture entering the bushing through leaky gaskets or other openings. Close periodic inspection to find leaks and make repairs if needed will prevent most outages due to bushing failures. High-voltage bushings, if allowed to deteriorate, may explode with considerable violence and cause extensive damages to adjacent equipment. All high-voltage bushings should be inspected periodically in intervals of 3-5 years. Bushings showing signs of deterioration should be tested at intervals of 6 months to 1 year and removed from service if the tests show a dangerous condition. Common inspection tests are power factor, radio-interference-voltage (RIV), DC insulation resistance, and oil or compound testing for moisture. The power-factor test is the most effective known field test procedure for the early detection of bushing contamination and deterioration. This test also provides measurement of AC current which is directly proportional to the bushing capacitance. Bushings may be tested by additional methods depending upon the type of bushing and the power-factor test set available [1]. Table 1 lists the common causes of bushing problems and the inspection methods used to detect them. According to table 1, most bushing trouble can be detected by measurement of power factor and capacitance of the bushings.

Table 1. Bushing problems

Trouble	**Possible Results**	**Detection Methods**
Cracked porcelain	Moisture enters, Oil and/or gas leaks, Filler leaks out	Visual inspection, **Power factor test**, Hot collar test
Deterioration of cemented joints	Moisture enters, Oil and/or gas leaks, Filler leaks out	Visual inspection, **Power factor test**, Hot collar test
Gasket leaks	Moisture enters, Oil and/or gas leaks, Filler leaks out	Visual inspection, **Power factor test**, Hot collar test, Hot-wire test for moisture, Insulation resistance
Moisture in insulation	Moisture enters	**Power factor test**, Hot collar test
Solder seal leak	Moisture enters, Filler leaks out	Visual inspection, **Power factor test**, Hot collar test, Hot-wire test for moisture, Insulation resistance, Leak detector
Broken connection between ground sleeve and flange	Sparking in apparatus tank or within bushing Discoloured oil	**Power factor test**
Voids in compound	Internal corona	Hot collar test, **Power factor tip up test**
Oil migration	Filler contamination	Visual inspection, **Power factor test**, Hot collar test
No oil	Oil leaks out, Moisture enters	Visual inspection, **Power factor test**, Hot collar test
Displaced grading shield	Internal sparking discolours oil	Hot collar test
Electrical flashover	Cracked or broken porcelain, Complete failure	Visual inspection, Hot collar test
Lightning	Cracked or broken porcelain, Complete failure	Visual inspection, Test lightning, arrestors
Corona	Internal breakdown, Radio interference, Treeing along surface of paper or internal surfaces	**Power factor test**, Hot collar test, Hot-wire test, RRIV
Short- circuited condenser sections	Increased capacitance, Reduced voltage at capacitance tap terminal, Adds internal stress to insulation	**Power factor test**, Voltage test at capacitance tap, Capacitance test
Darkened oil	Radio interference, Poor test results	**Power factor test**. Hot collar test

3 NON-INVASIVE CAPACITIVE SENSOR

NICS is a thin layer of conductor which is installed on the porcelain surface of the bushing near the ground potential (Figure 1)

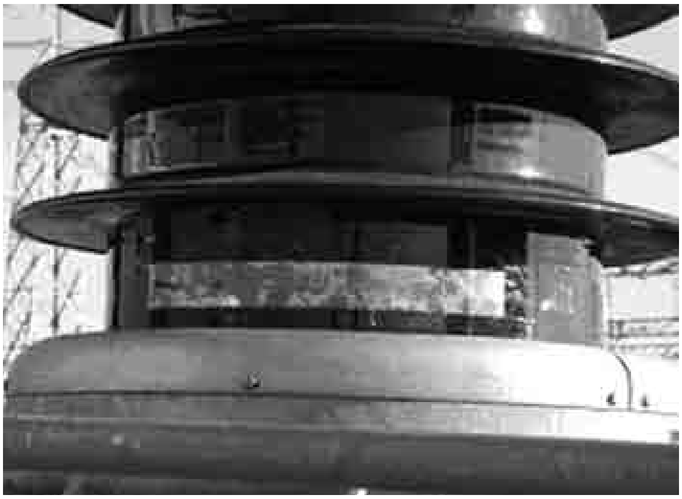


Figure 1. A copper strap was stocked upon the porcelain surface of the high voltage transformer bushing

This sensor forms a cylindrical capacitor with high voltage conductor through the layers of the bushing. The capacitance of the sensor could be calculated using the relation for the cylindrical capacitors (see Figure 2). The cylindrical capacitance of the outer conducting surface with the width of L is given by:

C NICS = 2__L / ln (R/r) (1)

_ is the permittivity of the insulation between the two electrodes, L denotes the width of the conducting strap and R and r are the outer and the inner radius respectively. If this sensor is only a sector of the cylinder with the length of S, the capacitance of it will be equal to:

C NICS = _LS/ R ln (R/r) (2)

To investigate the effect of the width and length on the performance of the NICS some measurements were carried out and reported in [2].

The voltage across each layer is V/N when V is the applied voltage of the bushing. Due to the very small capacitance of NICS (about 1pF) the voltage distribution of all the layers will not be influenced.

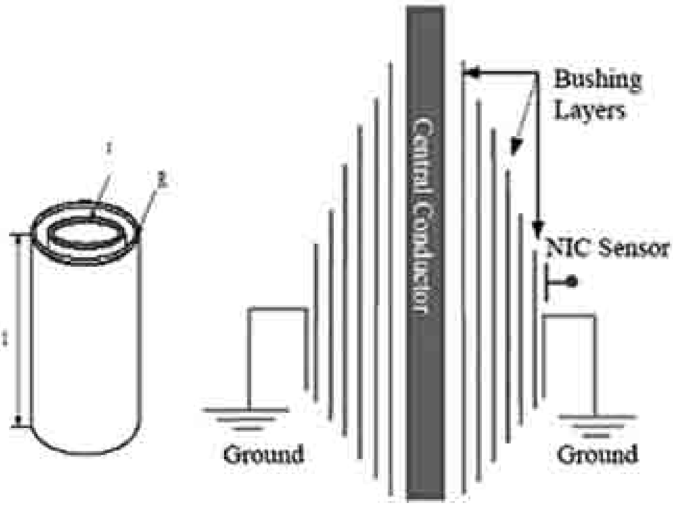


Figure 2. NIC sensor and cross sections of bushing layers

4 AIR GAP CAPACITIVE SENSOR (AGCS)

As shown in Figure 3, AGCS is a non-invasive capacitive sensor that is installed vertically near or on the porcelain surface of the bushing near the ground potential but it is isolated from the ground.

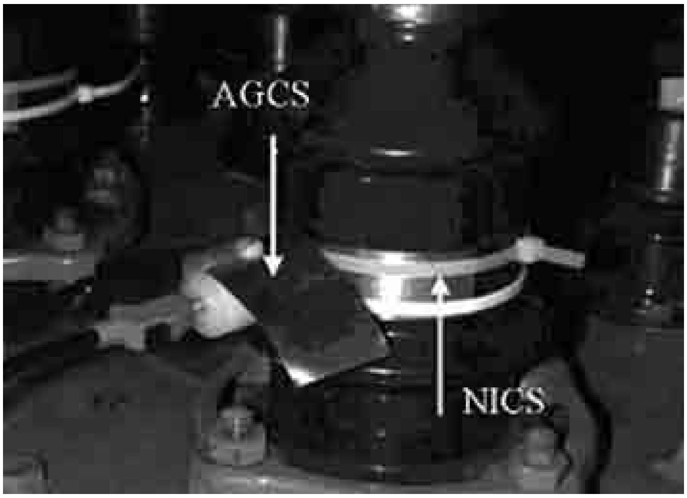


Figure 3. AGCS and NICS installed on a transformer

High-voltage conductor and AGCS form an air gap capacitor that can give a signal which is in the same phase with the voltage of the HV conductor and it can be used as a voltage reference. For evaluating the electrostatic field around the bushing where this sensor is installed, a HV bushing with 10 layers under 10kV voltage test is modelled with the help of electrostatic analyzer Quick Field software. As shown in Figure 4, the electrostatic field decreases between bushing layers from the central conductor to the last layer which is grounded. The bushing layers field does not have any effect on the outside of the bushing near the grounded layer. The electrostatic field outside the bushing is arisen only from the HV conductor which is outside the bushing. Referring to the same potential lines and the field vectors, this field is approximately vertical and can cause a voltage proportional to the HV conductor.

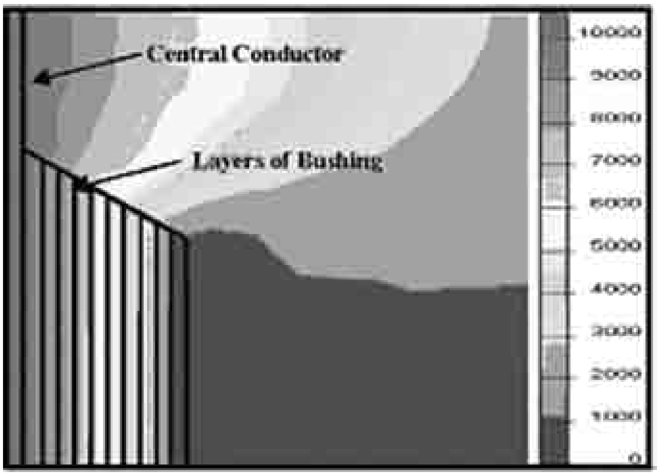


Figure 4. The equipotential surfaces of the electrostatic field of bushing and central conductor

5 PF&C CALCULATION

In Figure 5 the bushing from the bushing tap and AGCS are grounded through 1 nF capacitor. The voltages across the two 1 nF measuring capacitors are measured by a 2-channel data acquisition system. The input impedance of each channel is modelled with a parallel 32 pF capacitor and 1 MΩ resistor.

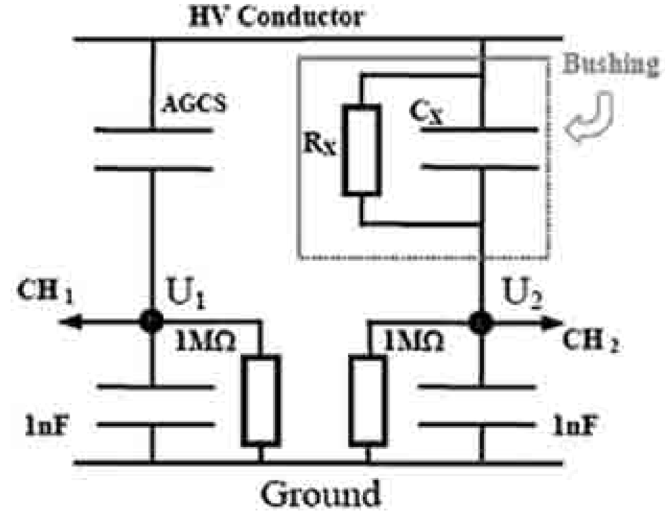


Figure 5. Equivalent circuit of measuring system (the capacitance of data acquisition system is not shown)

The equivalent impedance (Z_M) of C_M (the summation capacitance of 1nF and 32pF) and RM (1MΩ) of the measurement impedance and NC are calculated as below:

$$\text{Real}\,[Z_M] = R_M / (1+R_M^2\,C_M^2\,\omega^2) \qquad (3)$$

$$\text{Im}[Z_M] = -j\,(R_M C_M \omega) / (1+R_M^2\,C_M^2\,\omega^2) \qquad (4)$$

$$Z_N = -j / (C_{AGCS}\,\omega) \qquad (5)$$

The vectors U_1 and U_2 can be calculated to:

$$U_1 = [\,Z_M / (Z_M + Z_N)\,]\,.\,U \qquad (6)$$

$$U_2 = [\,Z_M / (Z_M + Z_X)\,]\,.\,U \qquad (7)$$

From the equations (6) and (7) the series equivalent impedance of the bushing will be calculated to:

$$Z_{XS} = (Z_M + Z_N)\,.\,(U_1 / U_2) - Z_M \qquad (8)$$

The voltage U_1 is considered as the reference voltage and the phase of the voltage U_2 is assumed as _. The quantity of U_1/U_2 is calculated as below:

$$U_1/U_2 = (U_{11}.\cos(\delta)/U_{22}) + j(U_{11}.\sin(\delta)/U_{22}) \qquad (9)$$

U_{11} and U_{22} are the amplitudes of U_1 and U_2. The tan _ and parallel model capacitor of bushing are calculated as below:

$$\tan\delta = R_{XS}\,.\,C_{XS}\,.\,\omega \qquad (10)$$

$$C_{XP} = C_{XS} / (1 + \tan^2\delta) \qquad (11)$$

6 MEASUREMENT UNCERTAINTIES

In order to determine the uncertainty of the measurement, the measurement of tan and capacitance of a paper capacitor sample were carried out with this method. This test was performed by a Schering-Bridge (model Tettex, sensitivity 5.10-7) and CPC 100 at 50 Hz too. The temperature was 25, 40, 60 and 80°C. The high voltage was connected to the sample through the bushing which was installed in the oven. The capacitor was equipped with a shield and grounded through the oven. The results are shown in Figure, 6 and 7.

These figures show that the values of tan _ and capacitance increase with temperature and the results of the Schering Bridge and the CPC 100 system are identical. The new method shows approximately the same behavior after calibration.

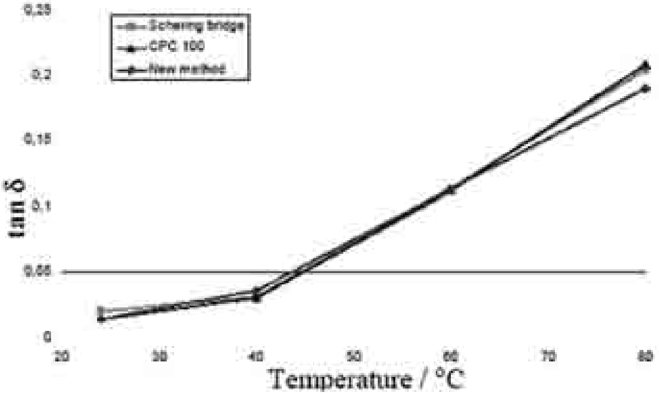


Figure 6. Comparison of measured tan with Schering The voltage U_1 is considered as the reference

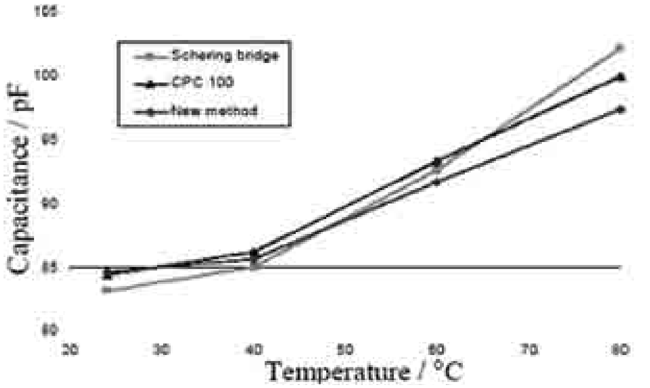


Figure 7 Comparison of measured capacitance with Schering Bridge and CPC 100 measuring systems

7 MEASURING SYSTEM

A 2-channel 8 bit A/D converter with a sampling rate of 250 kHz was used to detect variation of the amplitudes and phase difference of the two sensor output voltages from the bushing (NICS) and high voltage conductor (see Figure 8). The digitised signals are transmitted via an electrical link to a computer.

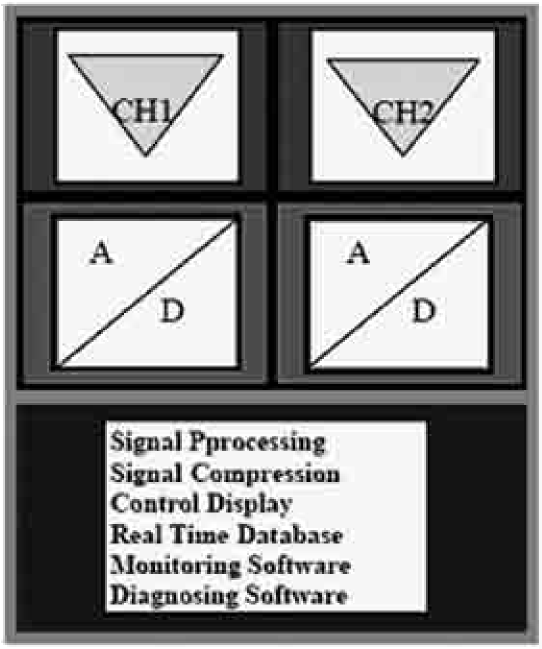


Figure 8. Power factor and capacitance measuring system

The continuously transmitted data streams of the two converters are sent to the digital signal processing units. The processor performs continuously the FFT (Fast Fourier Transformation) of the signals of each sensor to eliminate the noise. The dispersed quantities of the two high accurate measured voltage signals are transmitted in order to evaluate the amplitude and phase related to each signal after calibration of the sensors and to calculate capacitance and power factor. A real time database on the computer is continuously refreshed with the frequency selective quantities of the maximums value of each signal and phase difference related to the two signals. From the windows-based program platform, the user can see the variation of the power factor and capacitance of bushing.

8 PRACTICAL RESULTS

For evaluating the ability of this method, on-line measurement PF&C were performed on a multi-layered oil-pressboard capacitor (MOC) and a single-phase 420/13kV, 94 MVA power transformer.

8.1 PAPER AND OIL CAPACITORS

Whereas oil-impregnated paper was initially used as the primary electrical insulation in a high-voltage transformer's bushing, a MOC is considered as the sample (see Figure 9). By applying voltage to the sample and a NC according to section 5, the amplitudes and phase difference of the MOC and NC are measured (see Figure 10). Each layer of the capacitor has a connection, therefore short circuiting of layers is possible to simulate faults in the model.

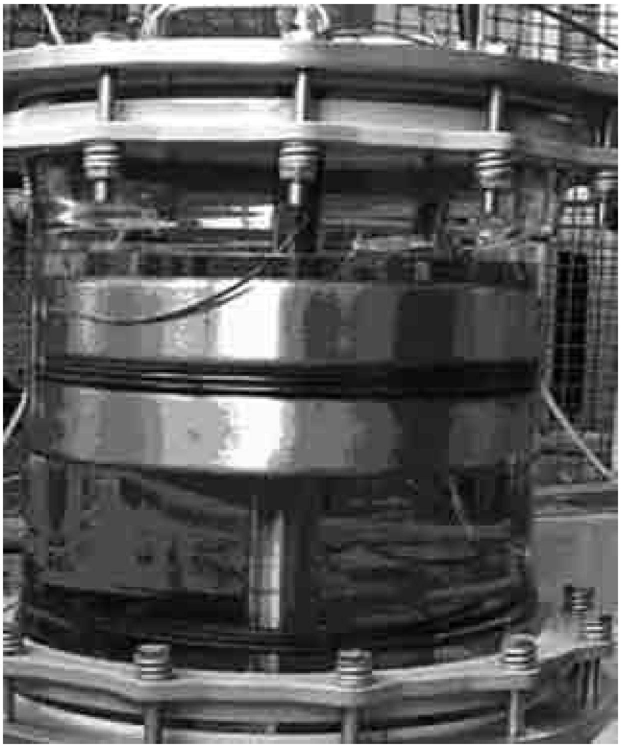


Figure 9. Multi-layers oil-pressboard capacitor

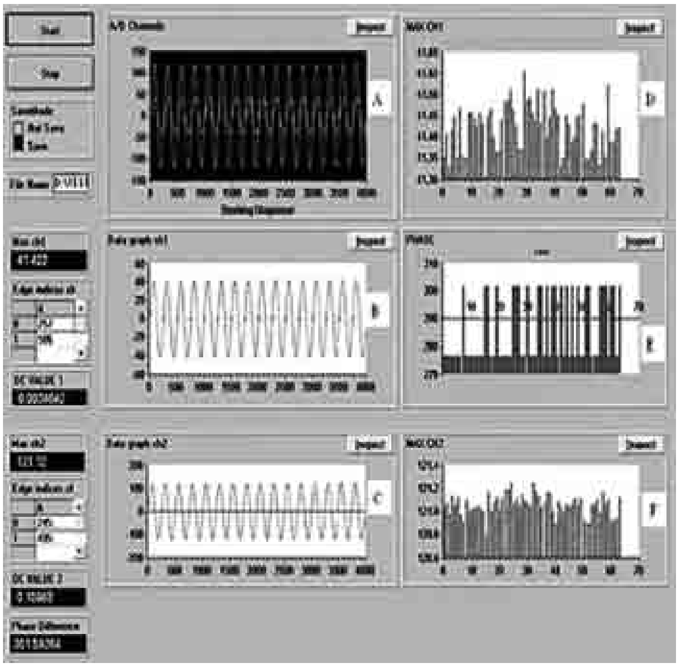
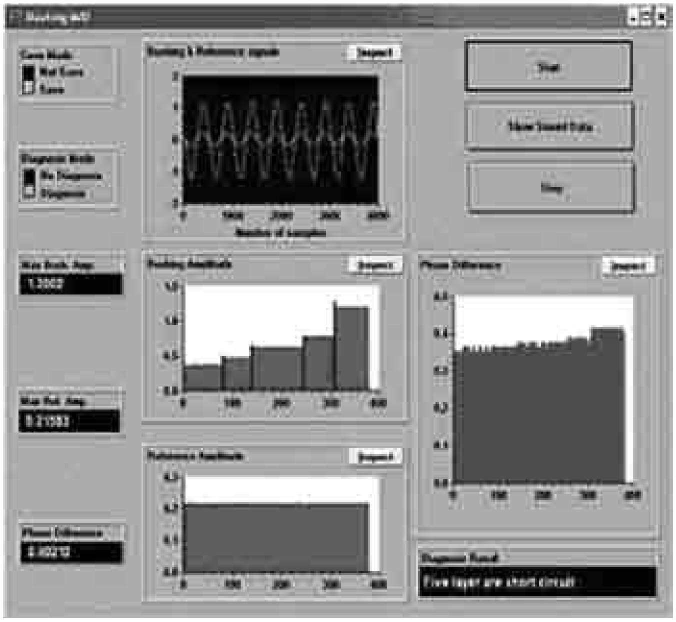


Figure 10. Windows-based program platform. (A) two voltage signals, (B) and (C) NC and MOC signals after filtering, (D) and (F) Amplitudes of NC and MOC signals in each sampling, (E) phase difference of the two signals B and C

8.1.1 ON-LINE FAULT DETECTION

For evaluating the ability to detect fault in the on-line condition of a transformer bushing, an artificial neural network (ANN) with the back-propagation model was used which has three layers of neurons: an input layer, a hidden layer, and an output layer. Five different cases are carried out for training the neural network. For each case, 100 data is entered to the ANN input and the network is trained with 500 input data to show 5 different cases. In the first case, operating is in normal state with no short circuit in MOC layers. The second case is with short circuit of one layer of MOC. The third, fourth and fifth cases are with short circuit of two, three and four layers respectively. The ANN output should have a value to show one of these five situations.

After training process, the software was used for monitoring and diagnosis of the MOC. All five case were tested to evaluate the software system. Thus normal condition and short circuit of different number of layers were performed to test the software. The software has distinguished all five cases successfully. Figure 11 shows the result of running the software after these five cases. There are five different data range (voltage level) for the oil-pressboard capacitor signal (graph B). The first range is for normal condition and the second to five levels show the amplitude of this capacitor signal after short circuiting one to five layers.



Five layer are short circuit

Figure 11. The software system, (A) Two measured voltage signals, (B) Amplitude of the MOC, (c) Amplitude of the NC, (d) Phase difference

8.1.2 ON-LINE MEASURING OF PF&C

For evaluating the feasibility of using this method as an on-line PF&C measurement system, the MOC was warmed by a heater between ambient temperature (about 22°C) and 80 °C. During this heating process tan and capacitance are measured. Figure 12 shows the results of these measurements.

8.2 POWER TRANSFORMER

This data acquisition system was installed on a power transformer in a manufacturer’s laboratory. Figure 13 shows the used connections and sensors. In Figure 14, on-line measured data of sensors is shown. The amplitudes of two signals and phase difference are approximately constant during the complete measuring time. The capacitance and tan of bushing were calculated according to section 5 of this paper and the results are shown in Figure 15 which demonstrates that the tan and the capacitance of the tested bushings remain unchanged and the values constant.

It should be noted, that a mean value of the of capaciance and tan should be taken into account in order to prevent errors from noise. As a result of this on-line measurement in a transformer factory it can be concluded that the developed measuring system each can be detect failures in real time.

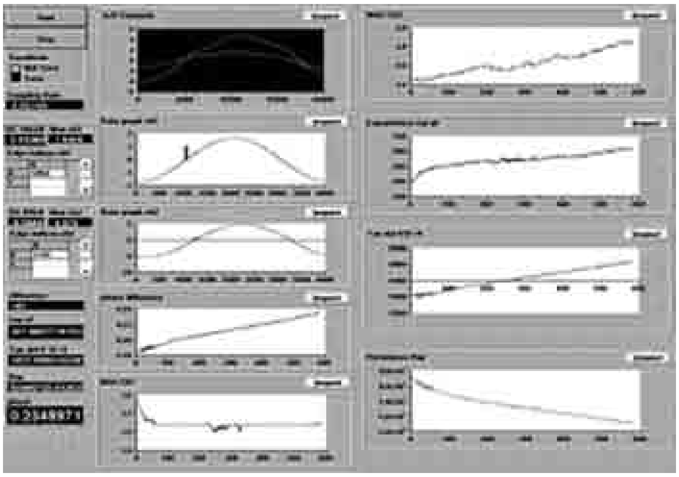


Figure 12. Windows based program platform. (A) Two voltage signals, (B and C) MOC and NC signals after filtering, (D) Phase difference (E and F) Amplitudes of NC and MOC signals in each recording, (G) MOC capacitance, (H) tan _ of MOC, (I) Parallel modelled resistance of MOC

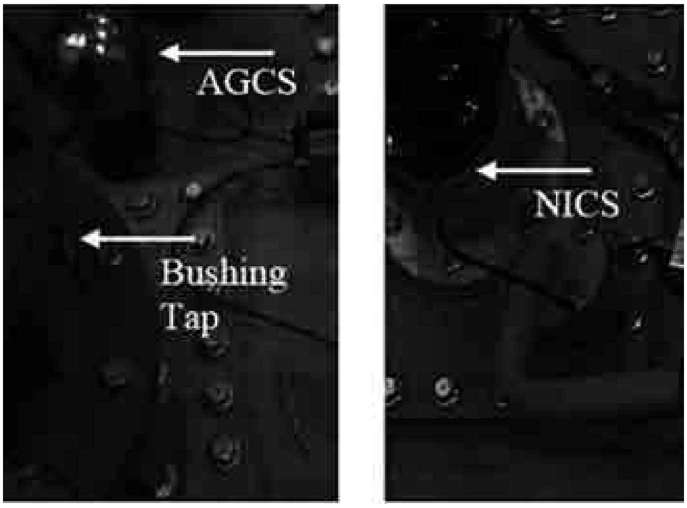


Figure 13. AGCS, NICS and bushing tap power transformer

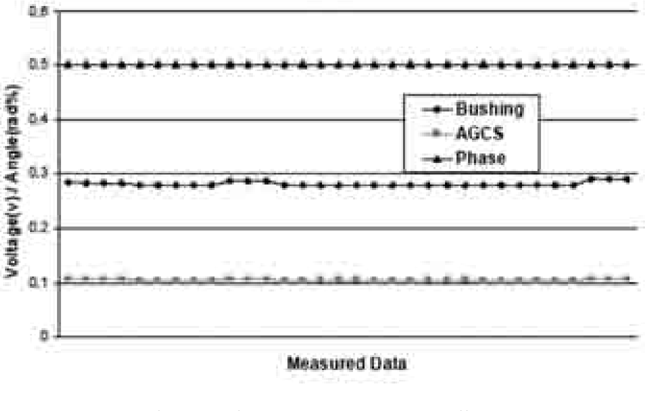


Figure 14. Amplitude of voltage of AGCS and NICS and phase difference

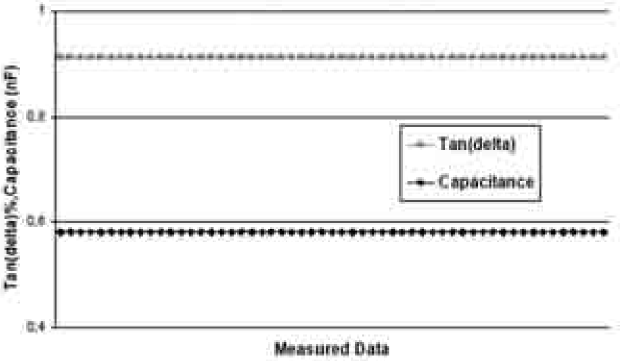


Figure 15. Measured tan _ and capacitance of power transformer bushing

9 CONCLUSIONS

Catastrophic faults power transformers. Off-line measurement of PF&C has been used by the industry and they are important for the reliability of power transformers but they need a remove of the transformer from service. The inability to identify serious changes taking place between test intervals is a significant problem for condition-based maintenance.

The proposed method with suitable sensors can detect the condition of transformers' bushings. Using adaptive sensors for transformers and a data acquisition system with high resolution) and accuracy will improve the system in transformer detecting the change in bushing condition more precise and reliable.

ACKNOWLEDGMENT

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AUTOMATIC IMPULSE VOLTAGE ROUTINE TESTING OF DISTRIBUTION TRANSFORMERS

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ABSTRACT

Distribution transformers are often produced by highly automated production lines. Overall factory throughputs for small transformers sometimes reach one unit per minute. This throughput requires a fully automatic impulse test system capable of generating and analyzing an impulse every few seconds. In addition, production information has to be integrated and verified by a host computer retrieving instantaneous pass/fail information from the impulse test system. High speed, high system reliability and correct pass/fail decisions are the challenges in implementing such an automated test system. In future, sophisticated analysis tools such as coherence and transfer functions with tolerance bands could be implemented. This allows a further refinement of pass/fail decisions which have to be investigated.

INTRODUCTION

Distribution transformers are exposed in their daily operation to transient over-voltages: impulses, which are due to atmospheric lightning or switching operations. Field experience has shown that these transients have certainly the most strenuous impact on a transformer's insulation and cause perhaps approximatly 50% of all premature failures [1]. Thus, international standards have long adopted impulse tests in their scope of tests.

Depending on the rated voltage, lightning and switching impulse tests must be carried out on each terminal of the test object. Since 1993, the L.I. test has also become mandatory for distribution transformers being tested according to ANSI/IEEE standards. US manufacturers are faced with the problem of testing each distribution transformer with impulse voltages (ANSI/IEEE Standard C57.12.90 [2]) to check manufacturing quality. Often running 3 shifts, 7 days a week, special features are required of the production line test equipment.

Haefely Trench AG has developed and delivered customized test systems designed to meet these specifications. A particular emphasis has been placed on the high transformer throughput rate, integration of state-of-the-art software tools and efficient communication between the customer's production line and the test system.

Figure 1 Distribution transformer (400 kVA, 20 kV ; from TESAR)

AUTOMATIC IMPULSE TEST SYSTEM

An automatic impulse test system for performing a complete impulse voltage test on distribution transformers (figure 2) has to fulfil the following requirements [3]:

- Long life expectancy
- Lowest cycle time
- Lowest maintenance
- Automatic report & test certificate generation
- Customized design according to client's specification and applicable standards
- Integration into manufacturing chain
- Automatic calibration feasibility [4].
- Safety features
- Design suitable also for unskilled operators
- Possibilities for off-line analysis of faults [5]

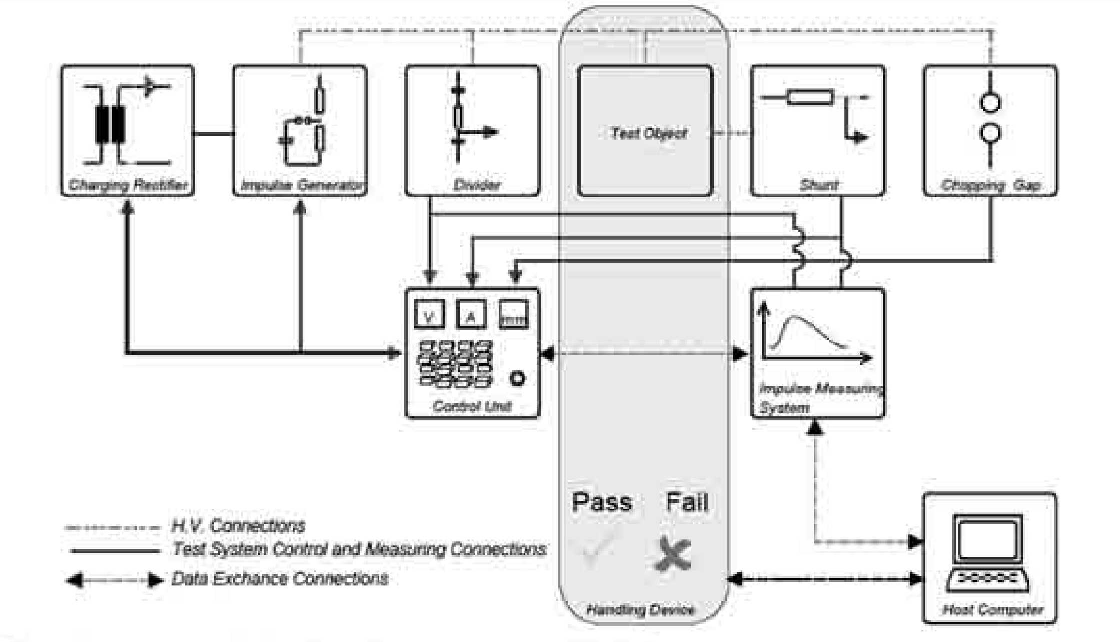


Figure 2 Automatic impulse voltage test system - block diagram

Figure 3 shows an impulse voltage test system that satisfies the above-mentioned requirements (total charging voltage 300 kV/15 kJ). A powerful charging rectifier, a fast sphere gap drive system and resistors with high energy receptivity allow to reach a cycle time between 3-10 seconds between the single impulses. A special design of the components allows a continuous operation of the system 24 hours per day for years with minor maintenance in-between. The control and measuring systems are customized and prepared for integration into the production line (figure 4). A design with a central host computer allows off-line analysis of the measurements on test objects with faults. Network connections enable the integration into quality systems.

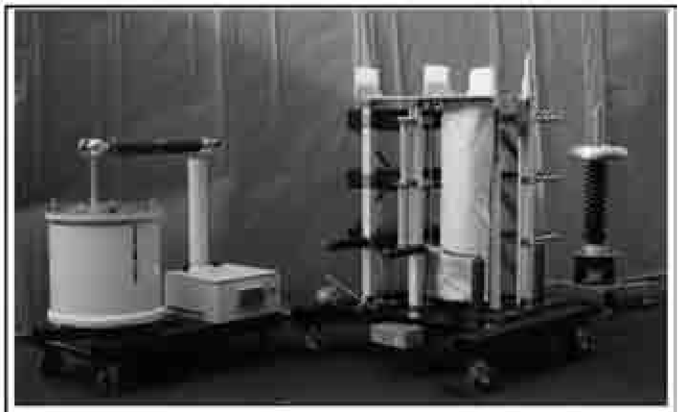


Figure 3 Impulse voltage generator with charging rectifier and divider

TEST PROCEDURE

According to the standards, the basic method for judging the results of impulse tests is the comparison between 2 test wave shapes, a reduced and a full level impulse. Figure 5 shows a typical test procedure for a comparison measurement on distribution transformers. The test object has to be identified (e.g. scan of a bar code), the control system inquires test levels, tolerances and pass/fail criteria from a database for the impulse set-up. At first, a reduced level impulse will be generated (e.g. 50%). Records of voltage and currents are taken. A check of the wave shape regarding tolerances is performed. The efficiency is calculated, a correction factor is used for the calculation of the charging voltage for the full level impulse test. After the wave shape check of the full level impulse, a normalization and difference calculation of voltage and current traces is carried out. The differences are the criteria for the pass or fail decision.

Figure 4 Control and measuring system

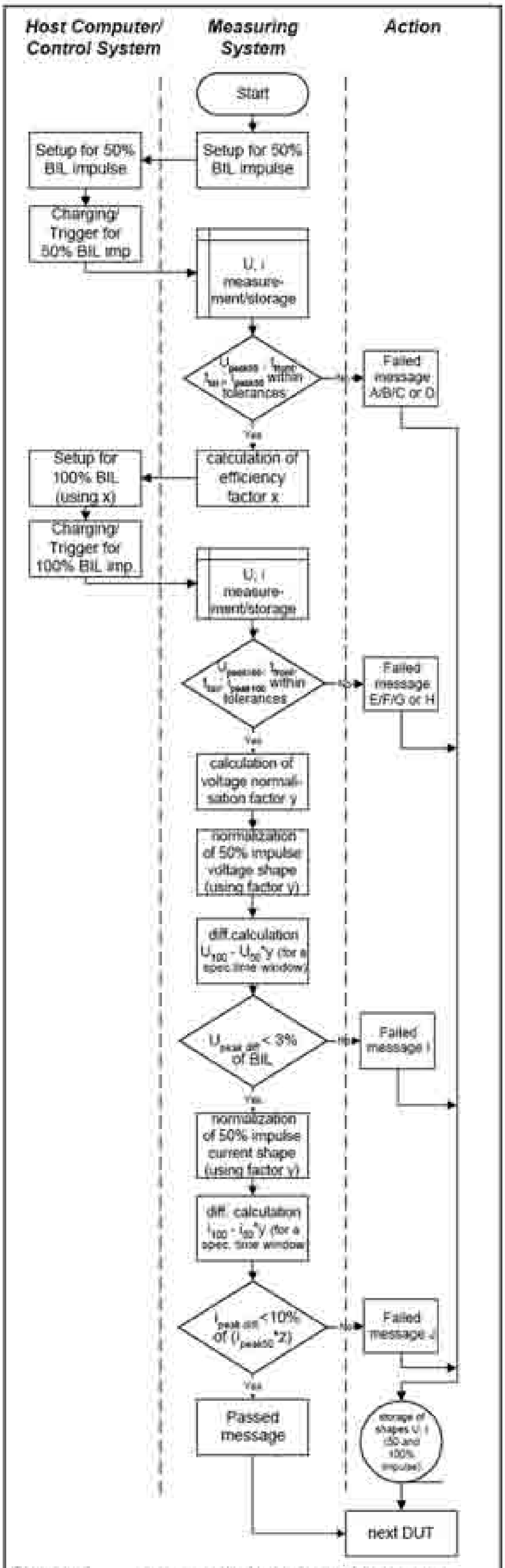

Host Computer/ Control System
Measuring System
Action
Start
Setup for 50% BIL impulse
Setup for 50% BIL impulse
Charging/ Trigger for 50% BIL imp.
U, i measure-ment/storage
Upeak50 , tfront, ttail , tpeak50 within tolerances
No
Failed message A/B/C or D
Yes
calculation of efficiency factor x
Setup for 100% BIL (using x)
Charging/ Trigger for 100% BIL imp.
U, i measure-ment/storage
Upeak100 , tfront, ttail , tpeak100 within tolerances
No
Failed message E/F/G or H
Yes
calculation of voltage normali-sation factor y
normalization of 50% impulse voltage shape (using factor y)
diff.calculation U100 - U50*y (for a spec.time window)
Upeak diff < 3% of BIL
No
Failed message I
Yes
normalization of 50% impulse current shape (using factor y)
diff. calculation i100 - i50*y (for a spec. time window)
ipeak diff < 10% of (ipeak50*2)
No
Failed message J
Yes
Passed message
storage of shapes U, i (50 and 100% impulse)
next DUT

Figure 5 Automatic impulse voltage test - flow chart

PASS/FAIL ANALYSIS

At present the maximum difference for voltage and current record are the relevant quantities for pass/fail decisions. The sensitivity to failures is generally different for the beginning, centre and end of a voltage or current record, the same is valid for the sensitivity to disturbances. As a result it is, in most cases, wise to select a certain time frame where sensitivity is optimal for fault detection and minimal for influences of disturbances. A typical comparison between a 50% and 100% L.I. measurement is shown in Figure 6.

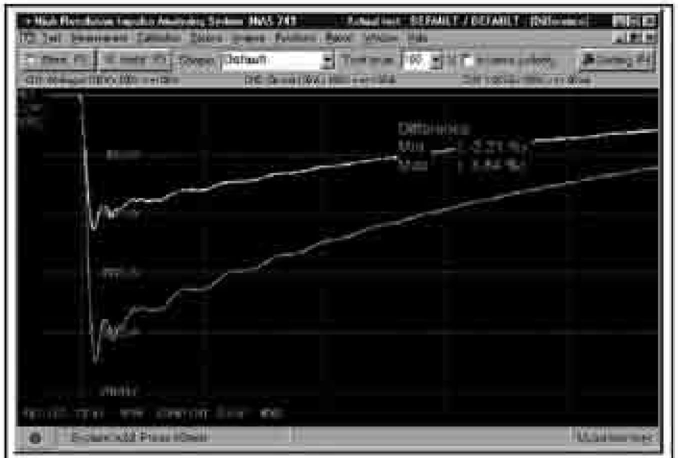
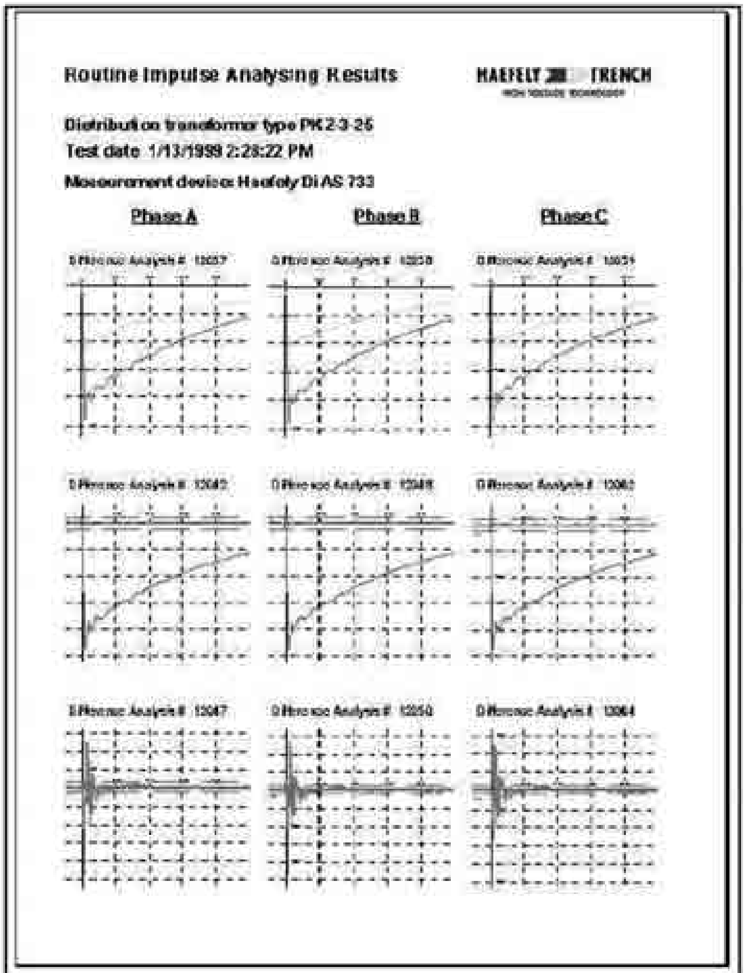


Figure 6 **Comparison of L.I. 50% with 100% showing both impulses and the maximum deviations numerically**

Change pass/fail analysis are primarily performed by comparison of measurements recorded with the same impulse shape but different voltage levels. Such a comparison is sensitive to voltage non-linearities of the test object. An example for such a non-linearity would be an internal "flashover" occurring at 75% B.I.L.. This failure is not affecting the 50% but strongly effecting the 100% amplitude measurement and therefore leading to non-linearities - clearly visible in the normalized difference calculation.

REPORTING

Depending on customer's requirements, reporting is very detailed for all transformers, or just a pass/fail list is printed. Failed transformers are often of higher interest as knowledge about actual errors can help the manufacturer improve his production significantly. However, quality standards require detailed documentation which may, in future, lead to more detailed reports in general. An example of a distribution transformer test report is given in figure 7.



Routine Impulse Analysing Results

Distribution transformer type PK 2-3-25
Test date 1/13/1999 2:28:22 PM
Measurement device: Haefely DiAS 733

HAEFELY TRENCH
Phase A
Phase B
Phase C

Figure 7 Example of a fully automatic test report. Shown are for all three phases the two voltage recordings, the voltage difference and the current difference calculation.

OUTLOOK

Insulation faults generally also show a very specific behavior in the frequency domain for which sophisticated analysis tools are available. For large power transformer testing ,Transfer Function [6] and Coherence Function [7] analyse have become well accepted already. However, the analysis of differences between two Transfer Functions is still requires skilled people and, so far, is not ready for automatic testing. A Tolerance Band Method for the Transfer Function [8] might allow using this tool for fully automatic transformer testing. Still though field experience is required and reliability has to be checked before implementing this tool.

CONCLUSIONS

Fully automatic impulse voltage test fields suitable for high throughput production lines have been successfully implemented. The required throughput, reliable passes/fails decisions and - most important - the desired reliability has been achieved. Several of these automatic test systems are continuously in operation for months generating and analyzing thousands of impulses without interruption.

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OPTIMUM REDUCTION OF POWER FREQUENCY MAGNETIC FIELDS FROM TRANSFORMER VAULTS

By: Jon W. Munderloh, Kenneth L Griffing, Michael L. Hiles, Per G. Forsgren and Kirby C. Holte

INTRODUCTION:

Substantial research exists regarding the characterization and reduction of extremely low frequency (ELF) magnetic fields associated with power systems. However, increasing sensitivity of computer monitors and other electronic equipment to ELF magnetic fields at low levels (3-5 mG) coupled with potential health concerns, has created interest in reducing magnetic fields from sources such as building transformer vaults to significantly lower values than is typical with conventional mitigation schemes. Traditional shielding methods typically lower field strengths into the 10 mG range. Power frequency magnetic fields from commercial transformer vaults are very difficult to mitigate to values of less than 10 mG due to the extremely complex character of magnetic fields produced by transformer vault components. This study evaluates methods to substantially reduce magnetic field levels from transformer vaults by installation configuration and passive shielding combinations.

OBJECTIVE:

Commercial buildings with internal large electrical transformer vaults commonly produce magnetic field strengths in the order of 10 to several 100 mG in spaces directly over or adjacent to the transformer room installation. Substantial magnetic field strengths in adjacent areas are usually complex in nature and are the result of multiple sources represented by the electrical components, wiring and connections present in typical transformer vault installations.

The objective of this study was (1) to closely characterize, in a full scale laboratory setting, magnetic fields produced by single- and three-phase transformers, their phase conductors and peripheral equipment as typically found in commercial building transformer vault installations, (2) to develop, test and document the effectiveness of configuration and installation techniques intended to reduce magnetic field strengths into the 3 to 5 mG range, and (3) to implement field reduction schemes at several commercial building sites to validate reduction techniques developed in the laboratory setting.

METHOD:

At a Southern California Edison Laboratory, a 20 ft x 16 ft measurement grid was marked on the floor to simulate the approximate size of a typical transformer vault. Three single-phase 500 kVA 12,000-480 volt transformers were placed in the center of the measurement grid in a linear array to form a three-phase 1500 kVA 12,000-277/480 volt transformer bank. The linear arrangement of such transformers is a widely utilized installation configuration by utilities throughout the United States. The test transformers were connected utilizing common industry installation practices to a 12,000 volt primary source. The secondary phase conductors were connected to bus and cable commonly used to connect secondary phase connectors to building electrical distribution equipment. All secondary circuit paths in the test set-up were connected together beyond the measurement grid area to create three-phase current circulation. This arrangement permitted 1,000 amps of current to be circulated through the secondary conductors to generate a wide variety of magnetic field conditions in the area of the measurement grid. Magnetic field spot measurements including x, y, z and resultant values were then taken at all measurement grid locations at 3, 6, 9 and 12 feet above the floor. These measurements provided a comprehensive view of magnetic fields present in areas immediately adjacent to and above the transformer arrangement. Close analysis of the test magnetic field measurement data provided the basis for design of an alternate arrangement wherein the three transformers were placed in a triangular or "delta" configuration to minimize secondary connection lengths and to promote natural cancellation effects. The triangular configuration of transformers was centered in the laboratory measurement grid and connected to the same test power system used for the linear arrangement. Magnetic field measurements were taken at the same measurement grid location at 3, 6, 9 and 12 feet to evaluate the anticipated field reductions.

After completion of the laboratory testing and evaluation of magnetic field strength reduction techniques, two "real world" sites with transformer vaults similar to the linear array laboratory transformer configuration were selected for field characterization and implementation of field reduction measures. A commercial building and a High School were selected for evaluation sites. Each site had linear array transformer vaults located underneath rooms with elevated magnetic field strengths present. Magnetic field spot measurements taken at these sites confirmed magnetic fields strengths in rooms above the transformer vaults were comparable to those noted in the laboratory.

It was not possible to reconfigure the linear array transformers at the two sites with the laboratory developed triangular arrangement. Wiring and installation modifications developed for use in the triangular configuration testing were implemented to improve natural cancellation of magnetic fields by improved adjacency of conductors. Using techniques previously developed in the laboratory, area shielding was also installed in the affected room above each vault, to insure that the average magnetic field levels were lowered to the 3 to 5 mG range.

LINEAR ARRAY TEST

In commercial building transformer vaults, it is common practice to arrange three single-phase transformers in a straight line to provide three-phase power. A neutral bus of copper strap is customarily attached to an adjacent wall to which the low-voltage neutral conductor from each transformer and the building load are connected to form the neutral (star) point. Low-voltage phase connections from each transformer are often oriented either perpendicular to or parallel with, the neutral bus often with significant separations between the phase conductors and the neutral bus bar. Also, the building (load) connection to the neutral bus is frequently separated from the phase conductors.

TRIANGULAR ARRAY TEST

In the triangular array test, the three single-phase transformers were repositioned in a triangular arrangement and the low-voltage connections from each transformer were oriented toward the center of the triangle. The neutral point (star) was created at a common location near the center of the triangle at which point the neutral load was also connected. The triangular arrangement of the transformers provided a very short neutral bus to form the common point with transformer phase leads immediately adjacent. The low-voltage phase conductors from each transformer were placed adjacent to the transformer and load neutral conductors. The triangular configuration assured that all conductors associated with the transformers were in close proximity to one another thereby optimizing natural cancellation of magnetic fields.

TEST SITE # 1

Excessive computer monitor distortion in several offices of this commercial building had caused the tenant to relinquish occupancy and use of the affected spaces. The affected offices were located directly above the building's basement transformer vault and main electrical switch room. Three 333 kVA single-phase transformers were positioned in a linear array with a neutral bus positioned on top of the transformer cabinets at some distance from the low-voltage phase conductors. Magnetic fields from net currents on a number of ground bonding cables and cable ducts were also documented. A magnetic field survey of the affected office areas confirmed that field characteristics present were generally approximate to the laboratory transformer linear array.

Due to physical constraints, it was not feasible to reconfigure the three single-phase transformers in a triangular arrangement. It was possible however, to relocate the neutral bus closer and immediately adjacent to the transformer secondary phase conductors. Additional grounding wiring reconfigurations and corrections were also implemented to minimize the presence of net current conditions. As projected, the neutral bus relocation and wiring changes dramatically reduced peak values and lowered the average B-field level in the office area to the 10 - 20 mG range. A layer of magnetic field shielding was installed on the office floor thereby further reducing the average magnetic field level to the 3 to 5 mG range.

TEST SITE #2

Elevated magnetic fields had caused the test site High School to abandon use of a large classroom located directly over the school's basement transformer vault and main electrical switch room. Three 250 kVA single-phase transformers were positioned in a linear array with low-voltage connections made to a series of exposed copper bus bars suspended from the basement vault ceiling. A comprehensive magnetic field survey of the classroom revealed that the bus bars were the primary source of elevated magnetic fields. Fields from net currents present on a number of ground bonding cables and cable ducts were also documented. The classroom magnetic field survey data confirmed that field characteristics present in the classroom was generally approximate to the laboratory transformer linear array.

Due to constraints, it was not possible to implement a triangular reconfiguration of the three single-phase transformers. Alternately, a custom robust multi-layer magnetic field shield was designed and installed around the suspended bus bars. Wiring reconfigurations and corrections were also implemented to minimize the presence of net current conditions. As anticipated, the wiring reconfigurations and bus bar shield dramatically reduced peak values and lowered the average B-field level in the classroom to the 10 - 20 mG range. A layer of magnetic field shielding was then installed on the classroom floor to further reduce the average magnetic field level to the target level of 3 to 5 mG.

RESULTS:

Analysis of laboratory measurement data from both transformer test configurations confirmed that secondary low-voltage phase conductors and neutral connections were the largest source of magnetic fields when measured adjacent to, and at various distances from, the transformer(s) location. Significantly elevated magnetic field values from the commonly used linear array of single-phase transformers were noted at a distance (15 to 20 feet) equal to an office over the vault. These elevated values appear to be primarily the consequence of large separations between the phase and neutral transformer conductors which result in poor self-cancellation.

The triangular configuration of single-phase transformers substantially improved the proximity of phase and neutral secondary conductors and minimized separations. Magnetic field values measured at 15 to 20 feet from the transformer were considerably diminished when compared to the linear transformer array measurements. The data suggests that magnetic field reductions of 50% or more can be achieved by compacting phase conductors and optimum arrangement of transformers. However, even after such compaction schemes, magnetic field strengths in the 10's of mG remain at a distance equal to an office over the vault. It appears from the laboratory experience, that further reduction of maximum fields to the range of 3-5 mG or less requires shielding in addition to reconfiguration options.

In both real world test sites, implementation of equipment reconfiguration measures and wiring changes improved natural cancellation between the low-voltage phase and neutral conductors, and yielded considerable reductions of magnetic field strengths in affected areas directly over each transformer vault. Magnetic field measurements at the two study sites however, confirmed that magnetic field levels in the 10 mG range remained as predicted from the laboratory testing.

The installation of large planes of conductive shielding on the floor of the affected area above the transformer vault at each test site successfully lowered the remaining magnetic field strengths to the 3 to 5 mG range as anticipated.

CONCLUSION:

The laboratory test data suggests that ELF magnetic field levels in spaces adjacent to commercial building transformer vaults are due primarily from the low-voltage load conductors attached to the transformers, rather than fields produced by the transformer(s). Magnetic fields at distances from transformer vault installations can be substantially reduced by electrical system design and installation modifications which promote natural cancellation among the transformer phase and neutral conductors. Even modest reconfigurations to bring the neutral bus in close proximity to phase conductors will cause substantial reductions in magnetic field values.

It appears from laboratory tests that it is impractical to achieve low (3-5 mG) magnetic field values exclusively by electrical system design and installation configurations which promote self-cancellation. The two test sites confirmed that lower values of 3 to 5 mG may be achieved by the careful use of sufficiently large planes of ferromagnetic and conductive shielding material when used in combination with electrical system design modifications which promote self-cancellation. Although elevated magnetic fields in commercial buildings are very difficult to reduce to low values, the test site installations demonstrate that it is possible. Equipment configuration and installation practices at the time of construction are the best options for managing magnetic fields from commercial transformer vaults.

ARC FURNACE TRANSFORMER FAILURES

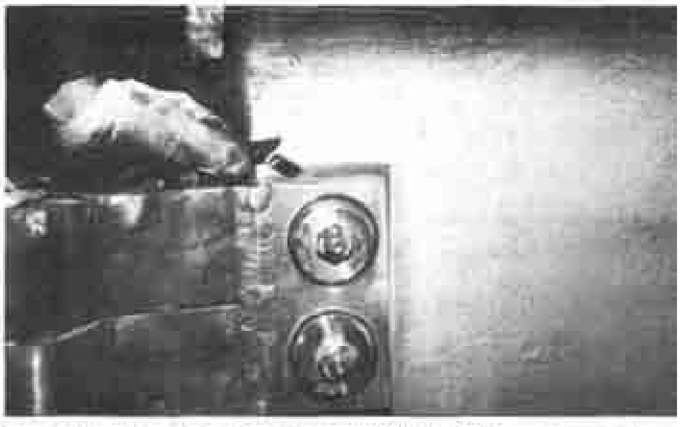
BROSZ AND ASSOCIATES

The electrical and mechanical duties imposed on transformers used in electrical arc furnace installations can be very exacting. The techniques of the operation and the unusual loads they produce are so severe, particularly on the transformer, that special design requirement and later, the maintenance of the units is essential. Recent examples of arc furnace transformer failures illustrate that it is possible in many instances for a forensic engineer to investigate and determine causes of failure, provided sufficient evidence is left.

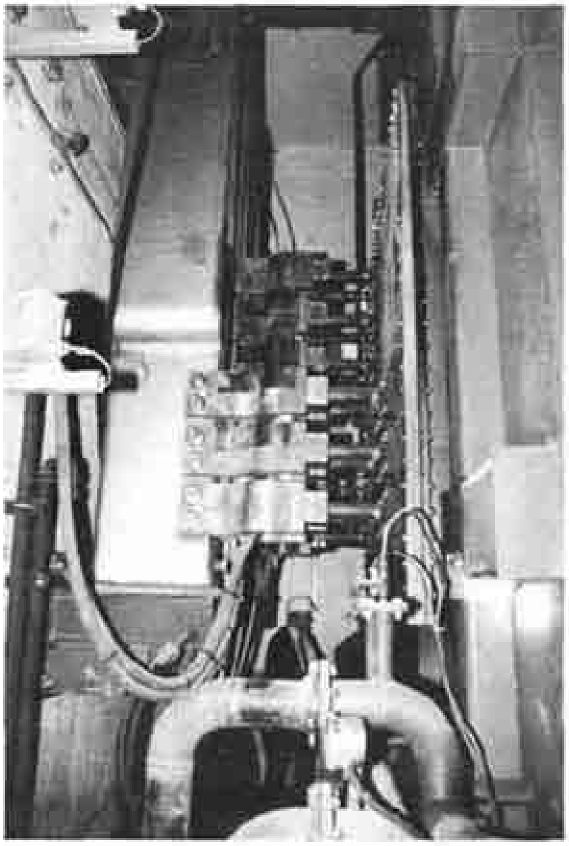
An arc furnace is primarily used for converting scrap metal pieces to reusable material. The scrap metal is loaded into a refractory lined bowl and subjected to an intense electric arc generated between moveable electrodes and the scrap material. Until the scrap material is reduced to a molten mass, the electrical loads imposed on the supply are severe and erratic. The melting process can typically require up to 100,000 Amps of electric current which will have superimposed on it, harmonic variations, which are wildly fluctuating, causing very unusual load patterns in the supplying transformer. This means that the arc furnace must have a supplying transformer which is custom designed to meet erratic loads for what will effectively be the equivalent of many short circuits.

The rough behavior produced by a vast succession or short circuits can be made even worse by mistreatment by the operator. For instance, when closing down the furnace, it should be normal practice to raise the electrodes first. Some operators will simply trip the control circuit breaker, resulting in considerable mechanical stress on the transformers.

In fact, many problems in arc furnace transformers can be traced to mechanical failures. Some of the failure analysis work on arc furnace transformers done by Brosz and Associates illustrates such problems as well as difficulties associated with overheating.



Close-up view of a defective 10,000 AMP bus connection. Note: Feeler gauge between mating surfaces.

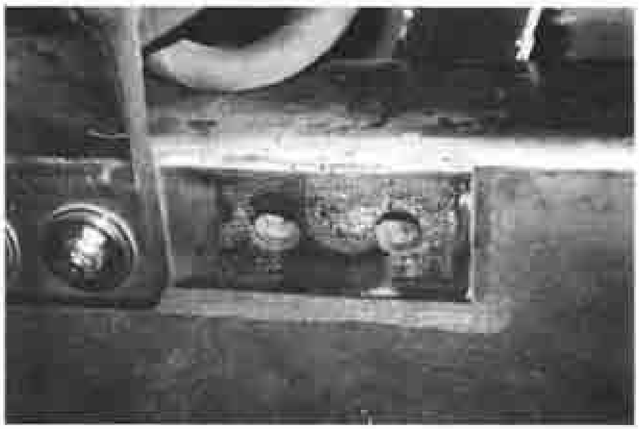


10,000 AMP Connections: Overheating on secondary (750V) side.

CASE I

On a particular 60,000 Amp, 750V, 50 Hz arc furnace unit the high current main connections to the furnace were found to have gaps between the connections. Severe burning and pitting found at 10,000 Amp rated connections was evidence of extreme heat. A feeler gauge could be pushed between the connection surfaces. The heat necessary to produce such pitting and burning had to be extremely high. This heat would be transferred to the transformer windings producing higher than normal temperatures in the winding and oil. This, with the eccentric duty of the system, combined to cause hot spots within the unit. Hot spots may lead to the deterioration of the insulation around the windings and sludging and the production of other contamination in the insulating oil.

Insulation failure, whether in solids or liquids will lead eventually to total failure and the loss of the unit. The lesson here is that all current connections must have maximum surface contact and run cool. Keeping highly fluctuating and sometimes severe overcurrent conditions within acceptable temperature limits will make insulation preservation easier. Installation checks to ensure good contacts added to knowledgeable preventive maintenance work, should aim for these requirements.



Close-up view of deteriorated/overheated 10,000 AMP water-cooled connection

CASE II

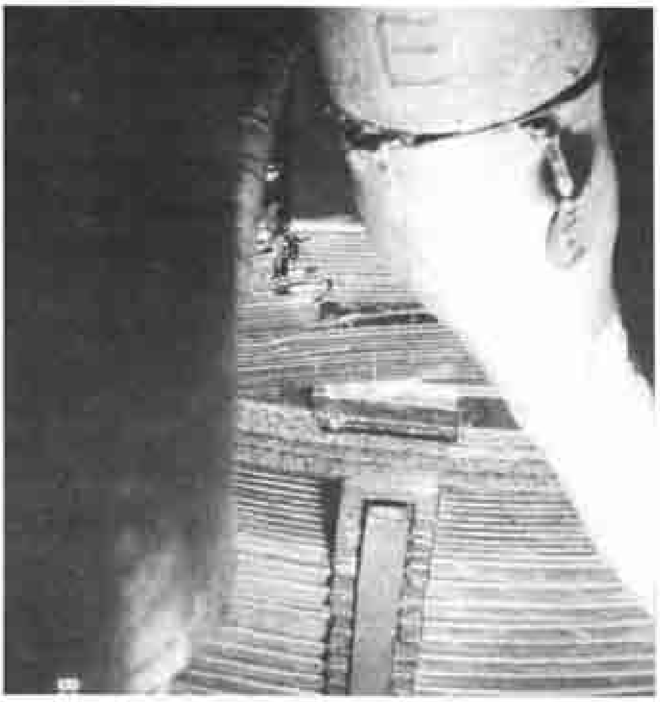
In another case, where the furnace transformer was designed using a shell form configuration, failure was due to the inability to control short circuit forces. This is unusual since shell form designs are always believed to be mechanically stronger than core form designs.

Shell form transformer windings are considered easier to clamp and hold down during short circuit behavior, but in this case the internal clamps loosened and did not hold and typical short circuit winding failures were found in the windings (see photo). Of course, the failure could have been due to extreme conditions within the general arc furnace circuit such as inadequate reactance, but, nevertheless, the evidence in this case suggested deficient clamping pressures.

Often, with continuous but erratic mechanical pummeling such as during the operation of the arc furnace, clamps can become loose and certainly release the original design pressures. Also windings tend to shift and shrink with age and the combination of this and tough mechanical pounding can add to the changing and deteriorating clamping pressures. The solution is to ensure during any maintenance inspection of the transformer that the clamping pressures are adequate and adjusted if necessary.

CASE III

A further problem was found in another transformer with loose extra flexible primary leads. Again, insufficient consideration of the mechanical forces set up by the tough conditions experienced by arc furnace transformers was found to be the reason why the flexible lead insulation became chaffed and worn, resulting in a short circuit fault.



Broken high voltage coil blocking. Due to short circuit forces.

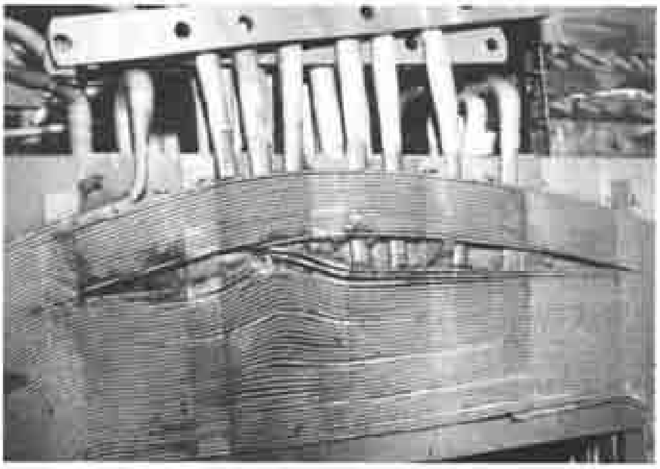
SOME SOLUTIONS

The solutions to preventing some arc furnace transformer failures will be found by considering what is happening to cause failure. It must be accepted that the loading of the furnace and the initial melt will set up abnormal conditions such as overvoltage, over-currents and harmonic distortion and these should be provided for in the general design. However, there is no escaping the fact that the result will still be mechanical pounding, high but fluctuating currents and voltage distortions. The basic requirements then are to guard against this by ensuring that currents are kept within design limits and to minimum proportions by ensuring good contact surfaces and tight connections. If possible, monitor the heat generated by the high current bars with thermal imaging systems or heat sensitive devices now available. Include, or check, the relaying system which protects against extreme over-currents and make sure such protection is adequate to give notice of early problems.

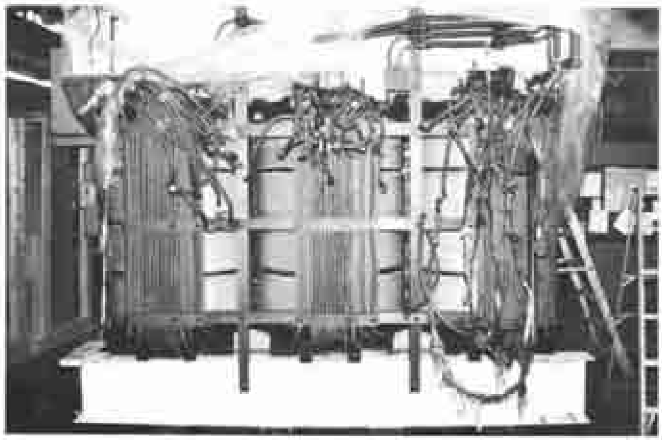
Internal inspection of the transformer should be carried out at least once a year by independent experts in conjunction with the manufacturer. Certainly the first year of operation is important because that will be the time when the greatest rate of changes such as relaxed clamping pressure may occur. In any internal inspection, all clamping should be checked and, if needed, retightened.

All leads and connections should be secured and every effort made to make sure nothing is loose. The windings should be checked for insulation deterioration whenever possible.

In shell form units, this is more difficult because of the particular construction; however, it may still be possible to make an inspection using boroscopes and similar devices.



Shell type furnace transformer. High voltage winding, turn-to-turn failure.



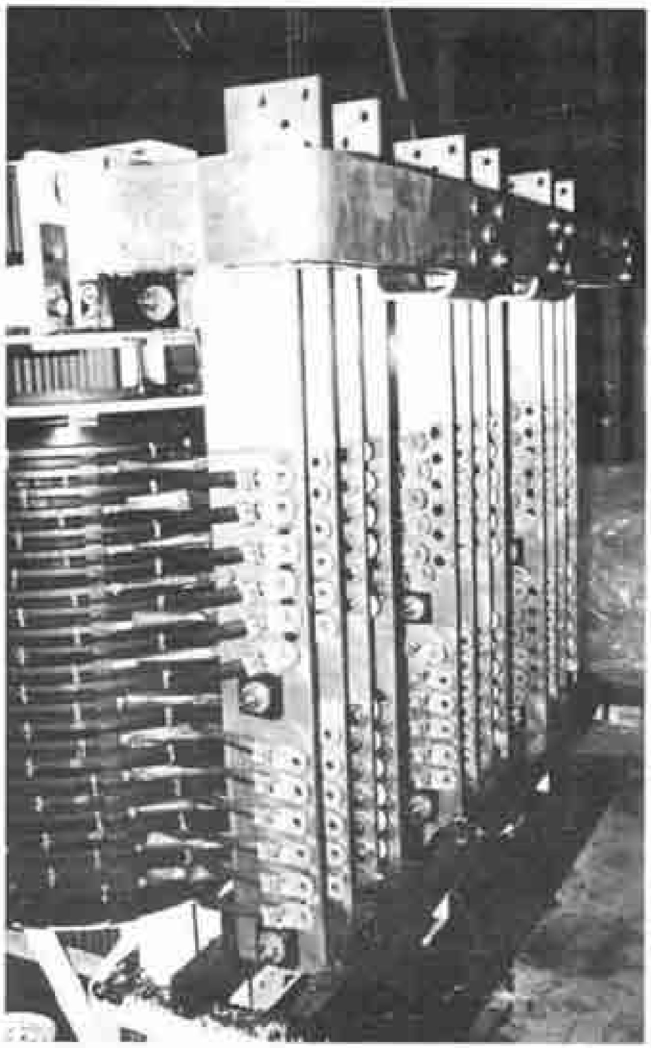
Failure of extra flexible, high voltage connections.

As with all transformers, the best method to check on their health is to check the condition of the insulating oil. The severe conditions experienced by furnace transformers can lead to oil contamination much quicker than conventional units. Even evidence of severe gassing will be found. Therefore, regular and more frequent oil analysis checks are recommended - at least quarterly. All the usual ASTM oil tests should be done and also regular dissolved gas in oil analysis is taken. This technique is probably the best reliability tool we have at the moment. In addition to measuring the degree of polymerization of the paper insulation, this measures the chemical by products of the insulating paper degradation. In addition, it is suggested that infrared thermographic readings be taken of the tank and the connections to give a clear understanding of the extent of external heating. Internal temperature measurements on energized windings can also be done using a specialized technique.

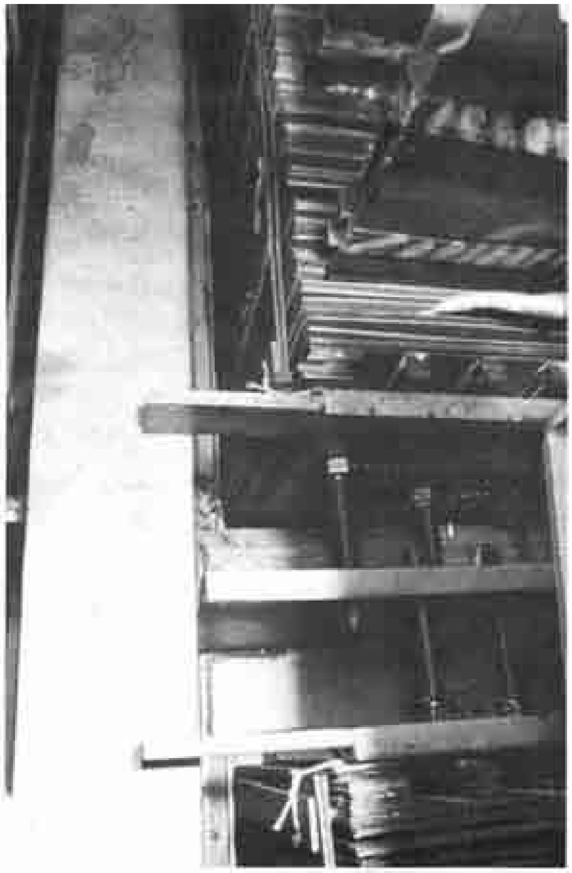
Another problem which is sometimes overlooked is the location of the arc furnace transformer.

The melting operation is not clean and if the transformer is located in an area where it can collect dirt and grime, especially on the bushings, then flashovers and insulator breakdowns can occur.

Ideally, these transformers should be located in a clean, sometimes air-conditioned and pressurized vault. Failures in arc furnace transformers are associated with high PD (property damage), high BI (business interruption) losses and large insurance deductibles. Professional independent inspection and diagnostics, taken on an ongoing basis, can go a long way towards reducing failures and eliminating unnecessary repair costs



Internal connection failure on 18 MVA transformer.



Shell form furnace transformer with loose core and shorted high voltage turns.

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TRANSFORMER FACTS AND MYTHS

Courtesy: Square D

TRANSFORMER FACTS AND MYTHS

The transformer industry recently has experienced significant confusion concerning non-linear load applications. For example, there is a common misperception in the marketplace that harmonic canceling transformers can correct non-linear current caused by computers, drives, HID lighting and other similar loads. The fact is, there are no devices that can prevent harmonic current distortion in downstream load panels and feeder circuits due to non-linear loads.

Attempts to prevent this will cause load equipment malfunction. Unfortunately, many manufacturers fail to make it clear that these products do not cancel the harmonics in downstream panels and load side neutrals and, in fact, may make load side harmonics worse.

K-Factor rating is another subject of enormous controversy. The method of evaluating transformers for K-Factor labeling is not supported by IEEE guidelines or standards. Yet, forces within the industry pushed through new standards by grossly exaggerating issues related to harmonic heating in transformers, neutral currents, the nature of non-linear loads, etc. As a result, overly high K-Factor ratings, and subsequent abnormally low impedances, were actively marketed in what became a “K-Factor rating war.”

Close examination reveals that many of these issues simply do not exist. But customers are not always specialists in harmonics. It’s quite easy for some to capitalize on the confusion and overemphasis on certain issues to sell products that are not appropriate for general specification or routine application.

It’s important to point out that the vast majority of all installations providing power to non-linear loads are successfully doing so with conventional designs using standard transformers, panelboards and wiring practices. Where exceptions are called for, reasonable and conservative engineering practices can provide the solutions. Customers should be wary of introducing elements into electrical systems that solve one problem – while causing worse ones.

HARMONICS CANCELLATION MYTHS

Third harmonic and other “triplen” harmonics are characteristic of single-phase non-linear loads, such as lighting and computers. Current distortion containing triplen components can cause elevated neutral currents, excessive neutral conductor voltage drop and other power quality problems. Many attribute overheating of transformers to “circulation of triplen harmonics in the primary Delta connection”. Actually, load current triplen harmonics cannot circulate in the Delta primary.

That misplaced notion evolved from the historic use of Delta tertiary windings in utility Wye-Wye transformers to circulate the triplen harmonic components of primary excitation currents. Third harmonic components of core flux will indeed circulate in a Delta connection on the core. However, computer load current harmonics do not originate from core flux. Since third harmonic currents from computer loads on three phrase Delta-Wye transformers are non-simultaneous (that is, current flows only on one phase of the secondary at any one time because of the limited conduction time of switched-mode power supply line rectifiers), they produce no zero sequence current and thus, no circulating current in the transformer delta windings.

ANSI/IEEE C57.110, “Recommended Practice for Establishing Transformer Capability When Supplying Non-sinusoidal Load Currents,” would certainly have provided for the extra losses of such circulating currents if they existed. In fact, tests show that the elimination of triplen harmonics can be simply thought of as pure canceling effect, creating no extra current or losses in the Delta side of the transformer. The phase angle shifts in a Delta-Wye transformer connection can prevent third harmonic and other triplens from transferring from the load side to the primary lines (see graphic C). Isolation transformers also can be employed to create neutrals close to loads to improve power quality.

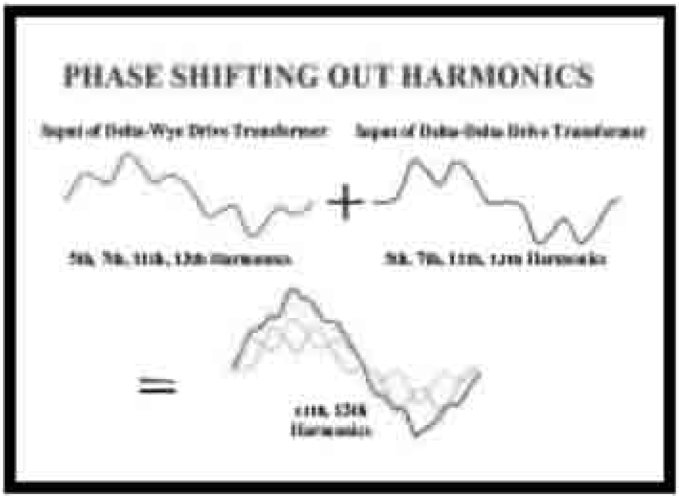
5TH AND 7TH HARMONICS

While standard Delta-Wye transformers are very effective in canceling 3rd and other triplen harmonics, additional connection refinements can be made to attempt to cancel 5th and 7th harmonics as well. Although standard Delta-Wye transformers pass 5th and 7th harmonics from computer loads back into the primary system, these harmonic levels are far lower than the same harmonics from drives and similar devices and are so negligible as to usually be of no concern.

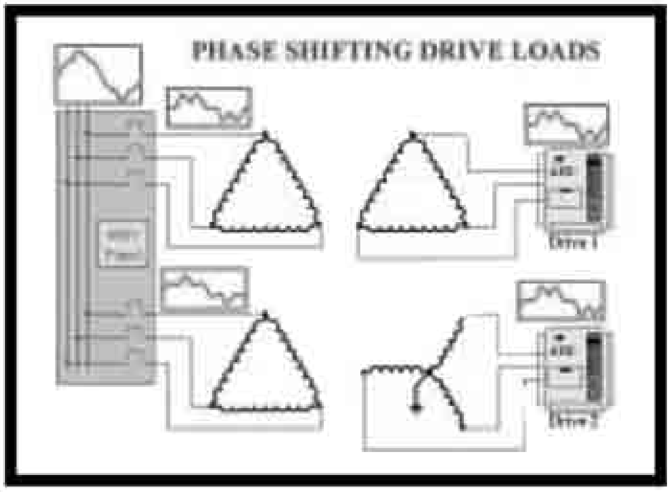
HARMONICS HIGHER THAN 7TH ORDER

Many vendors of “harmonic canceling transformers” also claim cancellation of 11th, 13th and even higher harmonics in computer loads. However, the simple fact is that harmonics above the 5th in a multi-computer load electrical system are at virtually random phase angles. Because of the random behavior of these harmonics, they do a good job of canceling themselves!

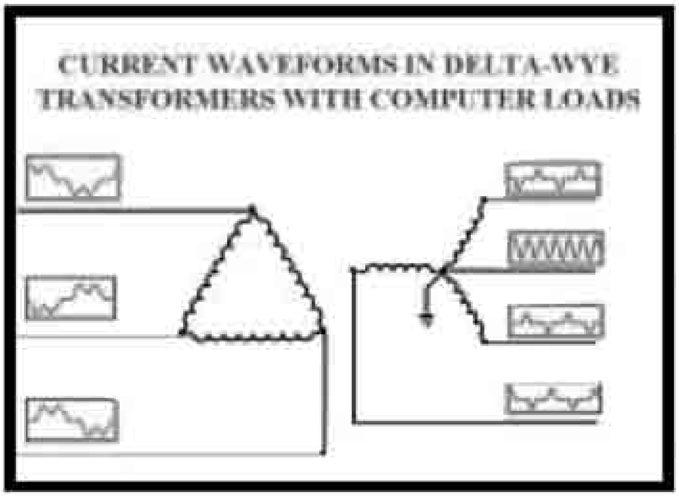
Manufacturers that promote products that “correct” circulation of triplen harmonics in the primary Delta connection or claim their products cancel above the 5th and 7th harmonics for computer and lighting loads are simply overselling the benefits of their products.


PHASE SHIFTING OUT HARMONICS
Input of Delta-Wye Drive Transformer
Input of Delta-Delta Drive Transformer
5th, 7th, 11th, 13th Harmonics
5th, 7th, 11th, 13th Harmonics
11th, 13th Harmonics

A



B


CURRENT WAVEFORMS IN DELTA-WYE
TRANSFORMERS WITH COMPUTER LOADS

C

THE MISUNDERSTOOD PHASE SHIFTING TRANSFORMER

Stated simply, phase shifting transformers do not cancel load harmonics. Their purpose is to prevent many of the major harmonics contained in that current from reaching the primary feeder side of the transformer.

Phase shifting transformers come in two basic varieties: multiple shifted output types capable of supplying between two and four load panels, and single output types to be used to supply parts of the overall system. Both varieties are available as either an isolation transformer or an auto-transformer. Regardless, they provide the same function – to execute the necessary phase shifts to reduce the amount of 3rd, 5th and 7th harmonics current transfer into the primary service.

These techniques have proven valuable in solving certain unusual problems with harmonic distortion effects. For example, this technique is used to reduce the amount of 5th and 7th harmonic current distortion caused by motor drives in industrial applications. Delta-Delta and Delta-Wye connected transformers provide the 30 degree phase shift between two balanced banks of drive loads necessary to dramatically reduce their 5th and 7th harmonic contribution into the service. In essence, such transformers can make two or more drives look to the primary service almost like 12 pulse devices, where the prominent 11th and 13th harmonic contribution is of much lower magnitude – and less likely to cause excessive system voltage distortion (see graphics A & B). There also are ways to provide this 30 degree phase shift in one dual output transformer to supply two drives or banks of drives.

Most of the phase shifting transformer products offered by the various vendors actually work to some degree, but it may surprise many to know that none of this is new technology. Square D has supplied such transformers for many years – since the first large-scale use of drives in the early 1960s. The only thing that is new is a change in the marketing techniques. Instead of making such products available for carefully considered applications and problem solving for which they have a value, there is an unsettling tendency among manufacturers to promote the general application of these products in areas for which there is little, if any, justification.

BEWARE OF NON-STANDARD TERMINOLOGY

Watch out for electrical characteristic terms that either do not have IEEE definitions, or are taken out of context by manufacturers. Terms such as “zero sequence impedance”. The intent of this phrase is to describe the “efficiency” of canceling out the triplen harmonics, which are zero sequence. There is no evidence that performance relating to canceling triplen harmonics has anything to do with zero sequence impedance, since the harmonics are canceled by opposing phase angles, not impedance attenuation. In fact, computer loads on three-phase wye systems actually draw current on only one phase at a time. Therefore, computer loads don’t even qualify as “zero sequence” loads! Look for these kinds of unusual performance claims and insist they be clarified by an IEEE or NEMA-sanctioned test or calculation method.

WHAT YOU SHOULD KNOW ABOUT TRANSFORMER IMPEDANCE

The Computer Business Equipment Manufacturers Association recommends that transformers supplying computer loads should have between 3 percent and 5 percent impedance. The higher limit is to prevent excessive voltage distortion and regulation; the lower is to make sure that enough impedance exists to limit crest factor, harmonics and neutral currents. Adherence to this rule can ensure neutrals on transformer mains and main panels do not exceed their rating.

Many "harmonic canceling" transformer manufacturers are ignoring this rule by providing abnormally low impedance in their products. They emphasize the supposed benefits of lower voltage distortion, despite the fact that up to 5 percent impedance transformers are successfully supplying high concentrations of computer loads throughout the world. In fact, less than 3 percent impedance actually can cause more problems than it supposedly solves, such as:

1. High Short Circuit Conditions - Let-through currents from transformers with less than 3 percent impedance can exceed transformer ratings by more than 33 times. Normal transformer construction cannot mechanically survive such current magnitudes. The magnetic imbalances created by more complex canceling connection schemes would need very sophisticated bracing to survive standard NEMA/ANSI short circuit requirements. Many small manufacturers do not have the resources to do full scale short circuit tests on their designs.
2. Additional Equipment Costs - High let-through currents from low impedance transformers can add expense to achieve higher interrupting ratings on secondary equipment. The higher load harmonic levels caused by abnormally low impedance transformers will make it necessary to use increased neutral conductors and special non-linear panels. In addition, within these panels one should expect breaker noise and nuisance tripping due to harmonic heating as a result of the abnormally high crest factors in the load current.
3. K-Factor - Impedance below 3 percent causes much higher secondary load harmonics, which leads to a higher than normal neutral current, and much higher K-Factor. For example, a 3 percent impedance transformer supplying high concentrations of computer loads will experience a full load K-Factor of between 3 and 6, while a 1 percent impedance transformer with the same load will see nearly K-20! Thus, it is even more important for manufacturers with low impedance products to list with UL for at least a K-20 rating.

Some manufacturers of "harmonic canceling" transformers claim that they replace K-Factor rated transformers. It is important to note that most of the primary and secondary windings of these transformers will carry the fully distorted load current. Harmonic cancellation occurs only at nodes of the connection points within the windings, usually on the primary side. Without a KFactor label, these transformers are not fully rated for non-linear loads.

DRIVE ISOLATION TRANSFORMERS – SOLUTIONS TO POWER QUALITY

By now it is well known that drives can cause harmonic voltage distortion and voltage notching that can lead to damage to other connected equipment. But what is not well known is that drive isolation transformers can be a simple, cost-effective solution to drives-related power quality.

Adding reactance to the drive's power source by using drive isolation transformers can reduce the amount of distortion present in the input current to the drive and can:

- Decrease line current waveform distortion, which improves the power factor of the drive load.
- Reduce voltage waveform distortion effects in the feeders ahead of the transformer, which can prevent drives from affecting sensitive loads, even other drives elsewhere on the service.
- Reduce line notching effects on the system voltage caused by SCR switching overlap.

Unlike simple line reactors, the secondary of a drive isolation transformer represents a separately derived power supply that is electrically isolated from the primary source. If the secondary is wye connected, then it can be grounded. Grounding prevents the transfer of common-mode noise and transients, both from the primary source to the drive, and from the drive to the primary system.

Drives can also introduce large induced ground currents. This is due to rapid current changes caused by diodes, SCRs, or pulse width modulated (PWM) outputs that couple currents capacitively through ground back to the source. High-frequency induced ground currents are a major cause of data disruption in digital communication and nuisance tripping of ground fault systems.

Introducing a grounded drive isolation transformer localizes the ground current effect and prevents it from extending upstream from the transformer.

When specifying drive isolation transformers, be sure they are designed to accommodate the additional heating effects of the distorted current of both AC and DC drives. Loads incorporating static diode rectification present distorted current waveforms to the transformer windings and can create additional heating in the coils. Three-phase SCR controlled loads introduce similar harmonic heating effects and present high-level current transients during overlaps. Drive isolation transformers also need to withstand the mechanical forces in their coils that result from SCR overlap current spikes, which are typical for DC drives.

Finally, the drive isolation specifier must consider thermal and mechanical stresses caused by the highly cyclic load demands of both DC and adjustable frequency drive process applications.

Many loads have characteristics similar to AC and DC drives. This is because the load inputs are either designed with three-phase static diodes or three-phase, 6- pulse, SCR bridge rectifier circuits. Drive isolation transformers can control the effect of these loads on the primary power system. General equipment applications for drive isolation transformers include SCR controlled heating or furnaces, three-phase rectifier input DC power supplies or three-phase switched mode power supplies.

SPECIFYING DRIVE ISOLATION TRANSFORMERS

There are no standards to differentiate transformers rated for drives from general purpose transformers. Many manufacturers merely re-label their general-purpose line for use as drive isolation transformers. To ensure your equipment is truly rated for drives, make sure the manufacturer is able to prove that the drive current distortion effects do not cause coil overheating.

In addition, IEEE Standard 597 requires that transformers rated for drives must be capable of supplying 150% of rated current for one minute out of each hour. In the case of DC drives, the manufacturer should have extensive field experience in providing coil design with adequate mechanical strength to ensure long life expectancy in high surge current applications.

Since one of the major benefits of using drive isolation transformers is to provide sufficient line reactance to reduce the effects on other parts of the electrical system, minimum reactance specifications are important. So, be sure drive isolation transformers you specify are:

Evaluated according to UL Standard 1561 or 1562 for effects of harmonic heating

- Designed for typical harmonics per IEEE 519-1992.
- Rated for 4% minimum reactance for 150°C temperature rise designs
- Built to IEEE-597 Class B overload standard, which requires 150% of load for one minute hour.
- Designed for the mechanical stress of DC drive current spikes.
- Designed for the thermal and mechanical stress of highly cyclic process control applications.

CREATING ENERGY EFFICIENT TRANSFORMERS FOR TRUE ENERGY SAVINGS

Nationwide surveys by the NEMA standards committee show average loading of installed transformers does not approach the level necessary to make investment in some currently available "energy efficient" transformers worthwhile. Statistics show that typical loading of low voltage, dry type transformers on a 24-hour average basis is only 35% of full load rating.

The data also indicate that the loading on medium voltage liquid and dry transformers typically averages only 50% of their nameplate capacity. At such loading levels, purchase of standard, low temperature designs with the intent of saving energy can actually result in a loss penalty.

NEMA has addressed this issue through publication of the "Guide For Determining Energy Efficiency for Distribution Transformers" – NEMA TP1. The guide defines minimum efficiency requirements to qualify for NEMA Class 1, and provides specifications for standardized calculation of transformer efficiency.

Low load loss transformers have been available in the industry for many years, providing substantial decrease in total energy loss at or near full load. Reducing the temperature rise of dry type transformers from 150°C to 80°C, for example, can reduce coil losses by 50% or more. The added winding material to bring about low coil loss, however, usually necessitates the use of larger cores with much higher core loss. Unless load levels are at an appreciable percentage of the transformer nameplate rating, the additional core loss will outweigh the advantage of reduced coil loss.

The key to providing truly energy efficient transformers, therefore, is to design the most efficient part of the transformer loss curve to match the average load that the transformer will realistically supply. Figure 1 shows losses comparisons of 75kVA low voltage, 150°C rise, 80°C rise and NEMA TP1 compliant dry type transformers. Note that the 80°C rise design will always be the clear winner at full load. However, the NEMA TP1 compliant design is clearly the most efficient at the 35% typical loading point.

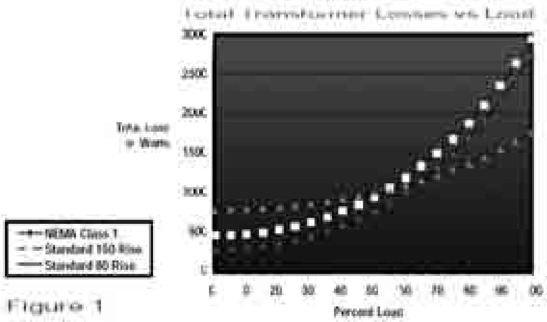


Figure 1

THE INDUSTRY CHALLENGE

The key task in converting the industry to truly energy efficient transformers is to design transformers complying with NEMA TP1 in such a way as to allow initial cost premiums for these products to be absorbed by energy cost savings within a reasonably short time. Typical designs for TP1 compliant transformers average a three-year payback based on $.06 per KWH utility rate.

Whether NEMA TP1 guidelines for transformer efficiency will be a voluntary standard, requiring the industry to promote energy efficient products, or it becomes a mandatory requirement for all transformers, is still undetermined. But saving energy saves money and saves resources, which could continue to change how we specify and purchase transformers.

Future commercial construction transformer sizing for 120 volt services will continue to see load disparities. The buildings will have many outlets placed for convenience per local codes. Many of the outlets will not see regular usage. The devices (eg: copiers, PCs, printers, monitors) that are normally plugged in are utilizing energy savings features while not in use. Thus the total transformer loading of these services over 24-hours on average can be as low as 35% or lower. The energy-efficient transformers will play an important role in tomorrow's electrical systems designs.

SOLVING NEUTRAL CONDUCTOR AND TRANSFORMER OVERLOAD PROBLEMS

The concern with harmonic producing loads is that they cause overloaded neutrals in transformers. For example, Figure 2 shows the neutral current resulting from a circuit loaded with personal computers. The maximum amount of neutral current for a personal computer load is 173 percent of the phase, although few systems reach this theoretical limit. For badly distorted phase currents (above 32 percent THD), the highest neutral currents occur with well-balanced phase currents. This is exactly the reverse of the harmonic-free state. Without harmonics, the current load on a shared neutral conductor is related to the amount of unbalance among the phase conductor currents.

So, why aren't there more electrical problems in commercial buildings related to this situation? To answer this question, the National Electric Code (NEC) formed an ad hoc committee to investigate the need for oversized neutrals. The committee found that neutrals sized to the same ampacity as phase conductors are overloaded in about 5 percent of the cases. This is due, in part, to the fact that few 208/120V systems are operated at full rated capacity. So, even if the neutral current exceeds the phase current, the conductor ampacity is not exceeded.

The second reason is explained by another NEC requirement for phase wires. This rule says that phase conductors (and overcurrent protective devices) cannot be sized smaller than 125 percent of their continuous load. Since the neutral is sized the same as the phase conductor in most cases, the real current-carrying capacity of the neutral is 125 percent of the continuous current in the phase wire.

TRANSFORMER LOADING

Standard transformers are designed to supply their full rated capacity under limited harmonic conditions. The standard to which transformers are designed says that they will transmit rated load at rated temperature rise when:

- Energized from voltages with less than 1 percent total harmonic distortion (THD).

- Serving loads with less than 50 percent THD current.

In today's electronic world, these two conditions often are exceeded. The problem comes in assessing the effects of high harmonic distortion on standard transformers.

When transformer windings carry AC current, each conductor is surrounded by an AC magnetic field whose strength is directly proportional to the magnitude of the current. Each metallic conductor linked by the flux experiences an internal voltage that causes eddy currents to circulate in the conductor. The eddy currents are dissipated in the form of heat, producing an additional temperature rise in the conductor. This type of extra loss in the windings is referred to as eddy-current loss.

Eddy-current loss in winding conductors is proportional to the square of the load current that produces the field, and to the square of the AC frequency of the current. Since harmonic currents contain high frequency components, the eddy current losses associated with harmonics can cause a transformer's design temperature rise to be exceeded before its nameplate kVA rating is reached.

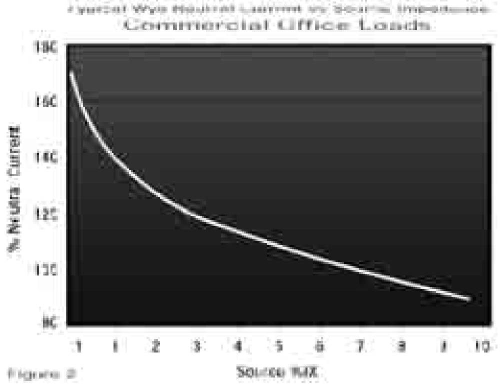


Figure 2

THE SOLUTION

If you are concerned about neutral overloading on a 208Y/120V circuit, what should you do? One solution is to increase the neutral current-carrying capacity by running a separate neutral wire for each phase wire, thus eliminating shared neutrals. Another way of increasing the neutral capacity is to replace a shared neutral with one rated for 200 percent of the phase current. The neutral buses on panelboards and transformers, however, may need to be increased as well.

While neutral concerns are easy to verify with power monitoring, the transformer loading issue is more complicated. The best method for dealing with harmonic currents in power transformers is to install k-rated transformers. They typically have additional coil capacity as well as reduced eddy-current losses. They can be wound with any standard primary voltage, and are usually supplied with 208Y/120 secondary. They can be supplied in any standard temperature rise, with electrostatic shields, and with either aluminum or copper conductors. Since these transformers usually serve computer loads, they also contain double-size neutral terminals to accommodate extra neutral wires. The higher the k-rating, the more harmonic current the transformer can carry.

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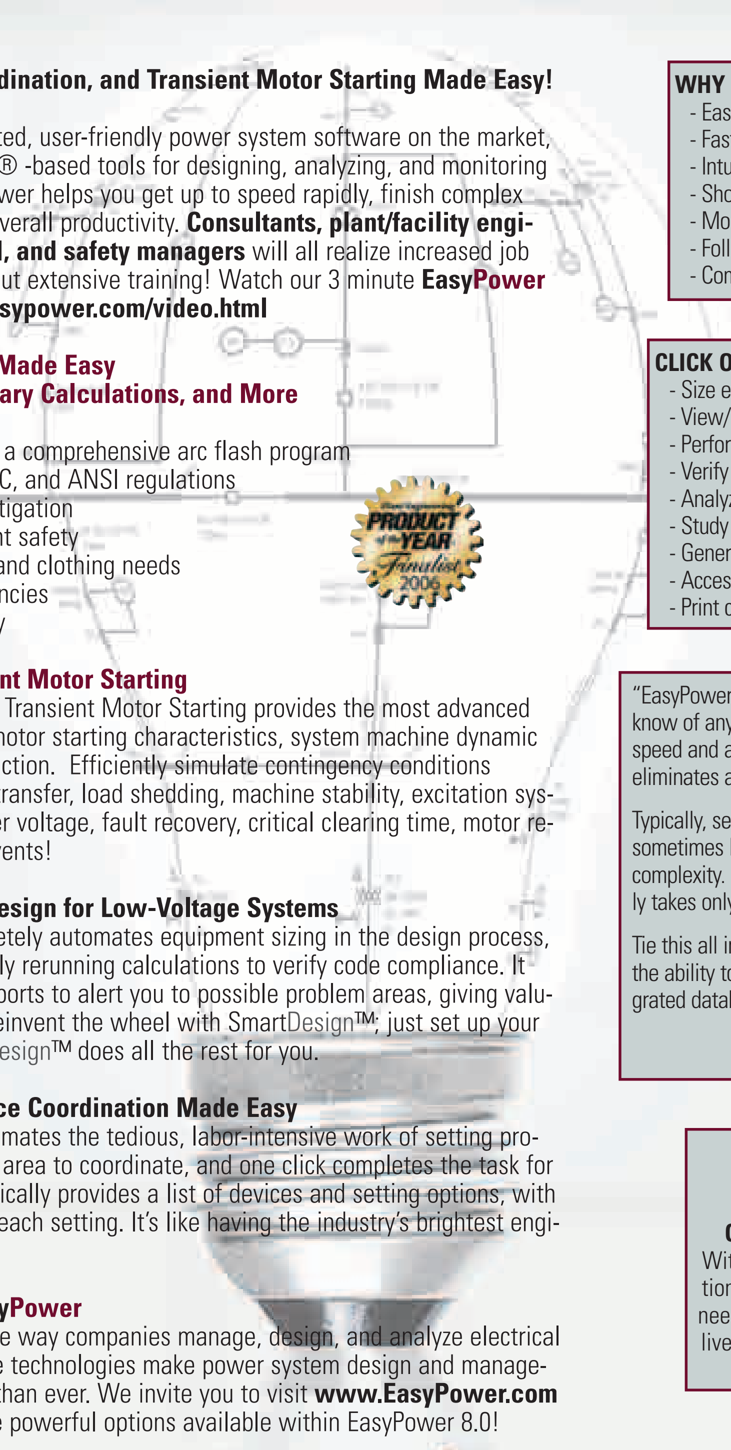

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  - Molded Case Breakers
  - QMQB/fusible switches
  - Combination Starters
- Emergency Service and Replacement Systems
- Design/Build custom Application Systems

NEOPTIX

Neoptix Fiber Optic Sensors, Inc.
1415 Charest Quest Suite 220,
Quebec, QC G1N 4N7
Tel: (418) 687-2500
Fax: (418) 687-2524
Email: info@neoptix.com
Website:www.neoptix.com

Neoptix Fiber Optic Sensors provides a complete range of fiber optic monitoring equipment for true and direct winding temperature monitoring of dry and oil-filled transformers. Neoptix temperature probes are ruggedized and designed to withstand manufacturing procedures, heat run tests and long term measurement. Monitoring systems are available with 1 to 512 channels, with most common communication protocols including serial, Ethernet, MODBUS, DNP 3 and IEC 61850.

OPSENS

2014 Cyrille-Duquet #125
Quebec City, QC G1N 4N6
Tel: (418) 682-9996
Fax: (418) 682-9939
Contact: Francis Raveneau, Sales Manager
Email: fr@opsens.com
Web: www.opsens.com

Opsens is a technological & market leader in the development & commercialization of innovative fiber optic sensors. The Opsens range of displacement, pressure, strain & temperature sensors are used in a wide range of applications, from laboratory use to applications like Aerospace, Medical & Energy.

Transformer manufacturers and Utilities alike have a special interest in our exclusive Zero-Fault™ sensors made specifically for transformer winding hot-spot temperature monitoring. Not only can they use Zero-Fault™ sensors to validate designs, obtain heat-run tests results and monitor critical & high-value assets but they can do so with total piece of mind: the Zero-Fault™ sensors are the only ones available on the market with a standard guarantee insuring 100% yield. This is why more users switch everyday to Opsens for their sensors. Please contact us to inquire if you are eligible for a free sensor trial.

Ad: USM-Permashell
1/4 page Vert. B/W
From the Electrical Tansformer
Handbook Volume 1
page 96

needs canges:
the line “the right way..”
has to be black
the line “the wrong way...” has to
be screened 60%

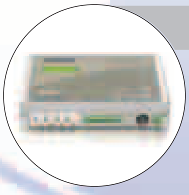
CHANGES WERE MADE
FOR VOLUME 3

Fiber Optic Temperature Sensors for Transformer Hot Spots

Neoptix offers a complete range of instruments, probes and accessories for temperature monitoring directly inside cast and oil filled power transformers

Nomad™ Handheld

Portable, battery operated
single-channel instrument, 1 GB datalogging
- *Ideal for heat-run tests* -



T/Guard™

Basic cost-oriented multi-channel (1 to 16)
system, LCD display, RS-232/485, MODBUS,
analog outputs, 1 GB datalogging
- *Ideal for connectivity to SCADA* -

T/Guard+™ System

Full featured multi-channel system,
1 to 16 optical channels, 16 Form-C
relays with galvanic isolation; MODBUS,
CANopen, OPC Server, 1 GB datalogging
- *The complete solution* -

➔ Now with 1 GB datalogging
on SD removable flash card

AVAILABLE ACCESSORIES

- T2™ TEMPERATURE PROBE FOR DIELECTRIC OIL
- TANK WALL OPTICAL FEEDTHROUGH
- NEMA-4 ENCLOSURE FOR YOUR INSTRUMENT
- EXTERNAL FIBER-OPTIC EXTENSION CABLES
- TANK WALL MOUNTING PLATE FOR FEEDTHROUGHS

ADVANTAGES

Accurate, direct temperature reading of winding's hot spots:

- Predicts or adjusts the dynamic loading of high voltage transformers
- Prevents premature failures
- Provides cost effective monitoring of transformer temperature

Extends transformer life:
- Helps estimate the insulation degradation rate
- Complements predictive hot-spot algorithm simulations

FEATURES

- **Tough and ruggedized sensors**
- **No gage factor or calibration**
- **RS-232/485, MODBUS, Ethernet, DNP3, CANopen and OPC Server available**
- **Voltage or current output**
- **Accuracy of ±1°C**
- **Systems available with 1 to 16 optical channels**
- **1 GB datalogging on all systems**

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www.neoptix.com

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